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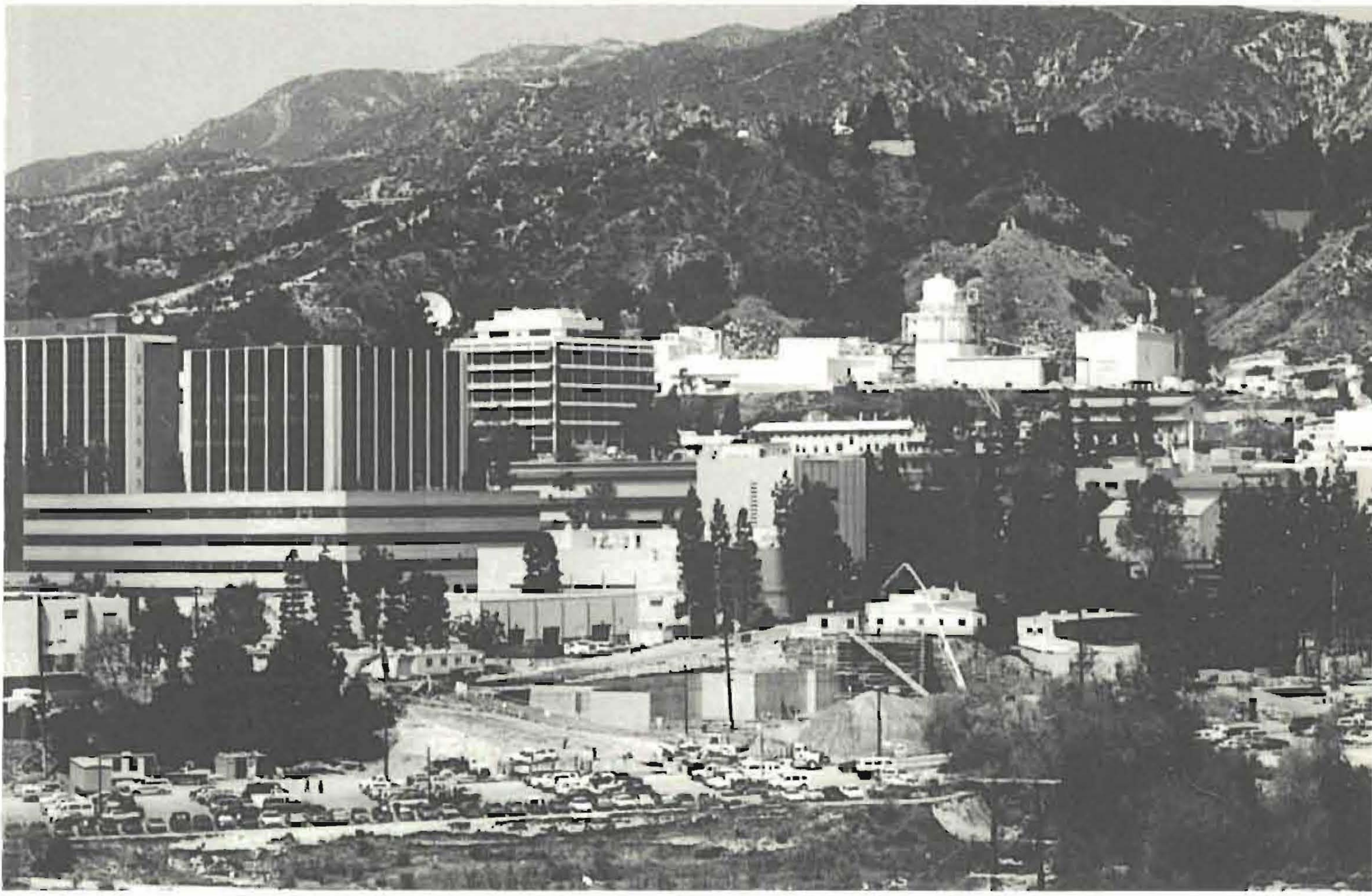
JET PROPULSION LABORATORY



1991

Annual

Report

82 pgs.
(inc. T. pg., i-iii, 1-78)

COVER: FROM MODEST BEGINNINGS NEAR PASADENA'S DUSTY ARROYO SECO, JPL HAS GROWN TO A 176-ACRE FACILITY COMPRISING OVER 155 BUILDINGS. IN THIS PANORAMIC VIEW, THE SAN GABRIEL MOUNTAINS FORM A MAJESTIC BACKDROP.

CONTENTS

A description of work accomplished under contract between the California Institute of Technology and the National Aeronautics and Space Administration for the period January 1 through December 31, 1991.

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

INTRODUCTION

The Jet Propulsion Laboratory (JPL), an operating division of the California Institute of Technology (Caltech), performs research, development and related activities for the National Aeronautics and Space Administration (NASA). The people of JPL share a common objective: exceptional basic and applied science and engineering work in support of the national interest.

The Laboratory's philosophy, missions and goals are distinguished by three characteristics:

- *The highest standards of scientific and engineering achievement: In keeping with its Caltech heritage and connection, JPL strives for excellence, objectivity and integrity in all its efforts.*
- *The lead role in the robotic exploration of the solar system: As a NASA field center, JPL is charged with responsibility for a broad range of major robotic planetary missions and space science instruments.*
- *The advancement of scientific and technical knowledge: As a Federally funded research and development center, JPL makes important, innovative contributions to the nation's scientific and technological vigor. The Laboratory carries out research not only for NASA, but for the Department of Defense and other Federal agencies as well. Many developments are also being shared with the private sector.*

JPL's role has grown significantly from the mid-1930s, when it began as a small university laboratory engaged in basic rocketry, through the 1940s and 1950s, when it played a major role in the development of U.S. Army ballistic missiles. The Laboratory became part of NASA on December 3, 1958, and its various flight projects over the last 33 years have provided the world with a fund of knowledge about every planet in the solar system except Pluto.

Today, JPL is an internationally known institution with an annual budget of more than $1 billion and a work force of more than 6,300 people. The Laboratory's charter continues to emphasize the robotic exploration of the solar system, but also includes key roles in space sciences, Earth sciences and advanced technology.

During 1991, the Jet Propulsion Laboratory enjoyed success in the management of a broad spectrum of activities for NASA, the Department of Defense, the Federal Aviation Administration and several other sponsors.

In flight projects, the Magellan spacecraft has nearly completed its second radar-mapping cycle of cloud-enveloped Venus, covering more than 95 percent of the surface. In the first encounter with an asteroid, Galileo returned images of Gaspra as the spacecraft continued on its journey to Jupiter. Ulysses, sponsored by NASA and the European Space Agency, was performing smoothly as it approached Jupiter for an early 1992 encounter. At Jupiter, Ulysses will be deflected into an orbit that takes the spacecraft into unexplored regions of the Sun. Finally, Voyagers 1 and 2 continue to operate and are exploring the outer regions of the solar system.

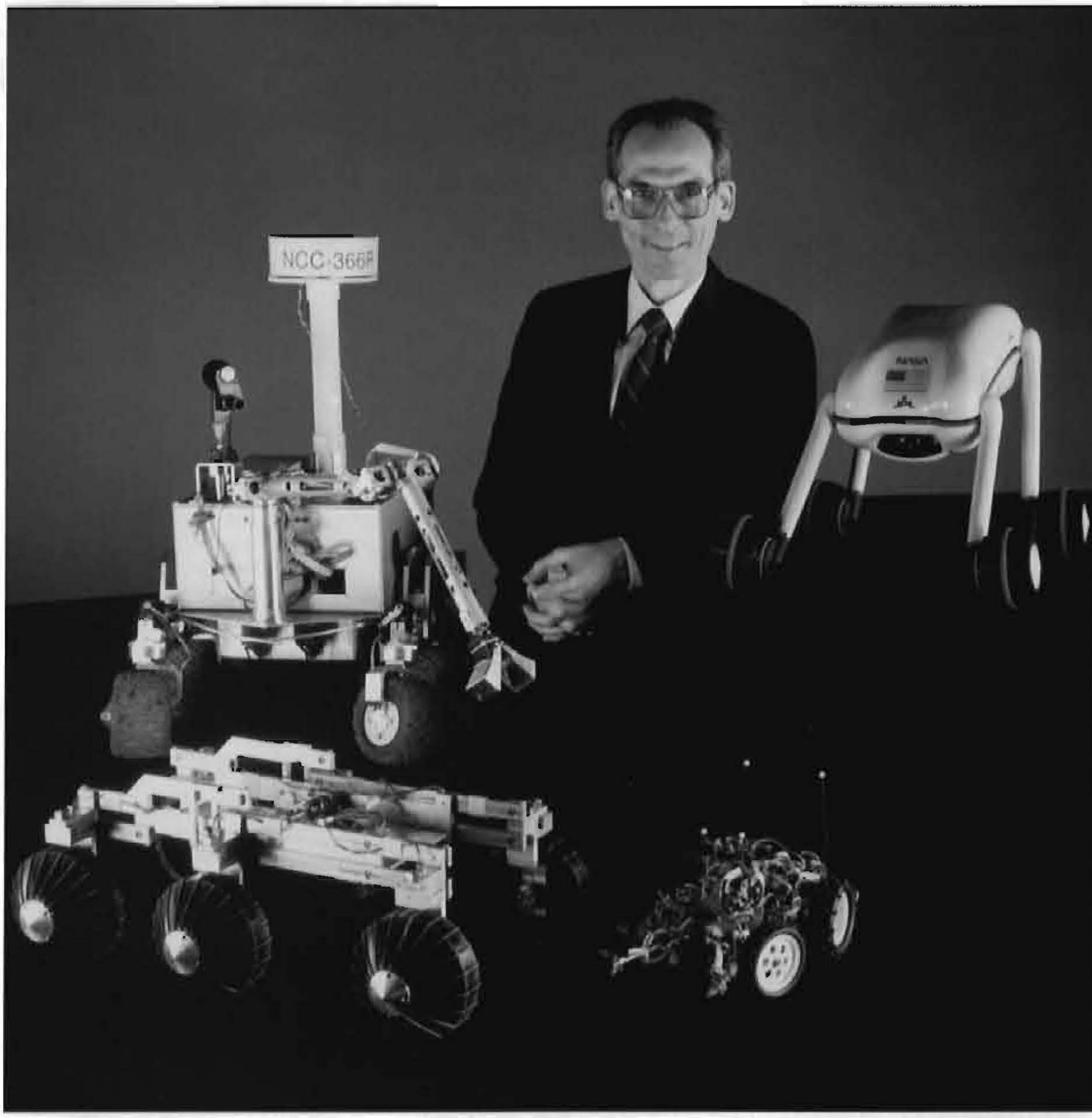
In space sciences, JPL instruments were flown aboard NASA's Upper Atmosphere Research Satellite, which returned useful data on ozone and chlorine monoxide concentrations in Earth's upper atmosphere. Other Laboratory instruments flew on aircraft missions; JPL components were also included in an instrument on a Japanese spacecraft that is measuring soft X-rays emitted by the Sun.

In advanced technology, the Laboratory continued its development of robotic microrovers and minirovers and was given lead responsibility by NASA for the Mars Environmental Survey (MESUR), a mission to land small packages of instruments on the surface of Mars. In supercomputing, JPL took possession of its upgraded CRAY computer and pressed on with research in massively parallel computation.

In all, 1991 has to be seen as a year of solid accomplishment for JPL.

E C Stone

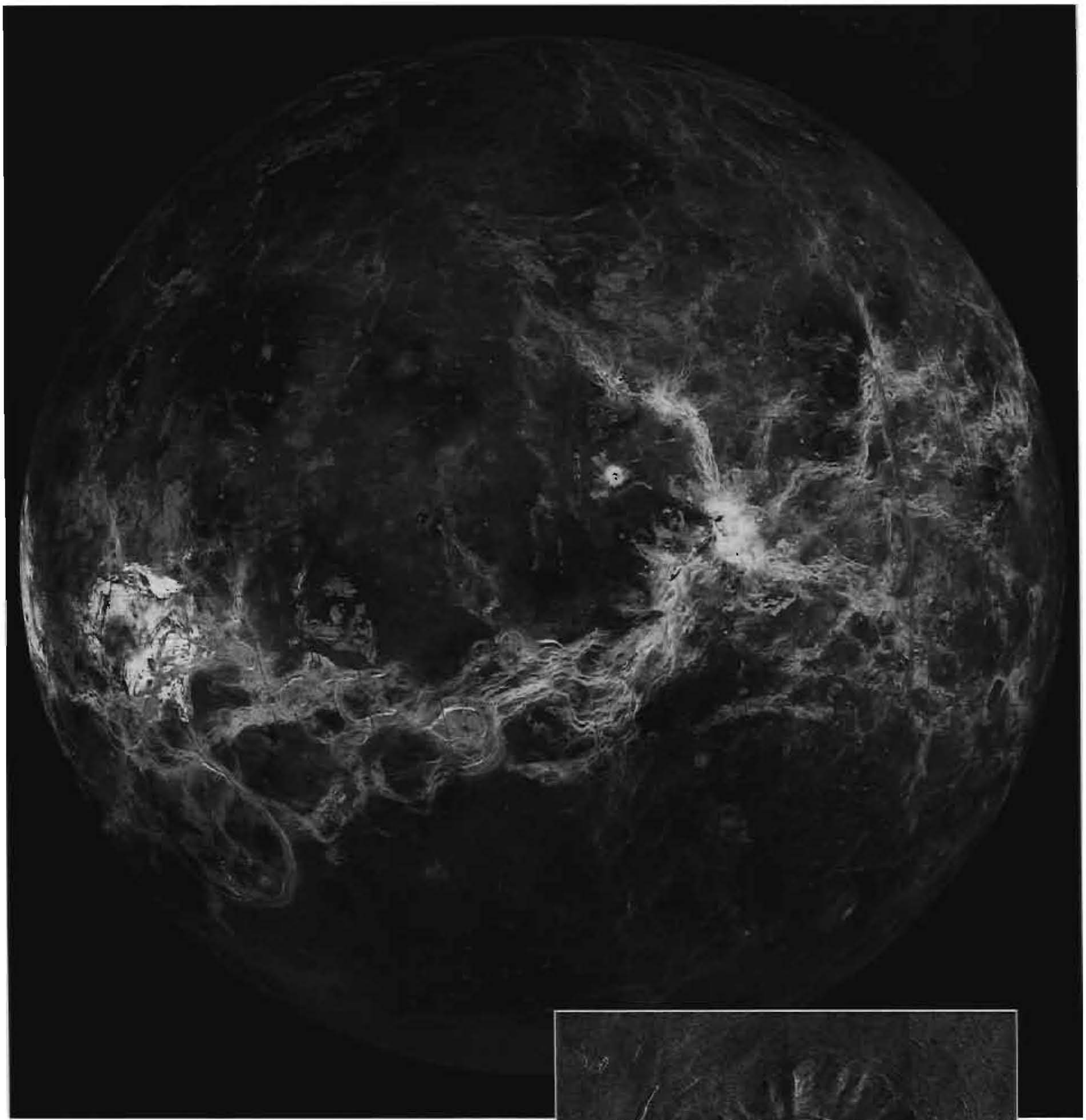
E. C. Stone
Director



DR. EDWARD C. STONE, JPL DIRECTOR, AND SOME EXPERIMENTAL ROBOTIC PLANETARY ROVERS. CLOCKWISE FROM UPPER RIGHT: GO-FOR, TOOTH, PANTOGRAPH AND ROCKY III.

JPL overcame *difficult engineering challenges* in 1991. The Laboratory prepared for forthcoming mission launches and deep space encounters while continuing to evaluate incoming data from the Magellan and Galileo spacecraft. Magellan's remarkable radar images *unveiled more of Venus and* its searing landscapes; Galileo's look at Gaspra, revealing a violent past, produced the first close-up pictures ever captured of an asteroid. Ulysses cruised to an encounter with Jupiter in early 1992 that will fling the spacecraft out of the ecliptic plane and send it on to a polar orbit around the Sun. *Flight teams pointed to* 1992 launches of the Ocean Topography Experiment (TOPEX)/Poseidon satellite and Mars Observer. Work on the two Comet Rendezvous Asteroid Flyby (CRAF)/Cassini spacecraft moved forward in anticipation of their planned *observations of asteroids and* a comet and investigation of Saturn. Meanwhile, Voyagers 1 and 2 were headed toward the outer boundary *of the solar system* in search of the heliopause, where the beginning of interstellar space can be sensed. Operating smoothly years beyond their expected lifetimes, both spacecraft continue their explorations *on behalf of humankind.*

ENGINEERS PERFORM VIBRATION TESTS ON THE GALILEO ANTENNA FLIGHT SPARE TO DETERMINE ANY RESONANCES THAT COULD BE AMPLIFIED TO FREE THE ANTENNA RIBS AND ALLOW THE DEVICE TO UNFURL.



MAGELLAN RADAR MOSAICS ARE COMBINED TO CREATE THIS IMAGE OF VENUS. INSET: A MAGELLAN MOSAIC OF A VENUSIAN VOLCANIC DOME.

MAGELLAN

Since the onset of its radar-mapping mission in September 1990, Magellan has traveled around Venus seven times each day in an elliptical, near-polar orbit, capturing images in parallel, successive, 21-kilometer-wide swaths. On every orbit, to maintain antenna-pointing accuracy for its telecommunications system and synthetic aperture radar (SAR), Magellan checks the position of two reference stars and updates its attitude-control computer.

Magellan's SAR has pierced Venus' dense, perpetual cloud cover to unveil volcanic domes, lava flows, rift valleys, complex faults, mountains and craters, along with evidence of wind-blown material and many other geological features. A sinuous river channel, 6,800 kilometers in length and averaging 1.8 kilometers in width, snakes its way across the Venusian plains. Probably carved out by molten rock, it is the longest such channel observed in the solar system.

The first Magellan mapping cycle of 243 Earth days (one Venus rotation) involved 1,680 orbits and covered 84 percent of the planet's surface. At the end of the first cycle, in mid-May, only two gaps in coverage remained: an area within 10 degrees of Venus' south pole, which was beyond the radar's viewing angle, and another area that was rendered inaccessible when Earth and Venus were on opposite sides of the Sun and solar emissions disrupted communications. The south polar region was imaged by switching the radar antenna to a "right-look" mode; the other area was mapped in left-look mode when it next rotated under Magellan's scan.

By the end of the second cycle, in January 1992, Magellan will have imaged some 95 percent of Venus' surface. An adverse thermal environment, previously predicted by mission planners, limited mapping in the second cycle — the spacecraft had to be cooled during part of each orbit by shading the electronic components behind the antenna dish. The adverse environment should diminish by the following cycle.

For additional insight into volcanic topography, Magellan scientists created "stereo pairs" by overlapping images from varying angles. The technique has proven to be so successful that a third mapping cycle will be devoted largely to stereo coverage of 70 percent of Venus. A fourth mapping cycle will focus on global gravity; the information should help clarify mass-density distribution on Venus' surface and could help resolve conflicting theories about Venusian geology. A fifth mapping cycle, commencing in May 1993, will move Magellan into a circular orbit for high-resolution global radar and gravity observations.

The raw data transmitted by Magellan are processed and converted into photographic images at JPL's Magellan Radar Data Processing Facility. The quantity of Magellan data processed at the facility has already surpassed the combined volume of data from all previous NASA planetary missions. The facility's primary SAR processing unit is one of the fastest in use; technicians are examining enhancements that might further improve Magellan's image-data fidelity and elicit even more high-resolution, topographic, surface-classification and stereo information from radar output. Magellan's views of Venus are disseminated by the National Space Science Data Center and the Regional Planetary Image facilities; over 30 compact disks have already been released.

Magellan has provided the first clear views of Venus, and evaluation of the data should begin to solve some of

the planet's many mysteries. Venus and Earth have been called sister planets because they are similar in size, composition and density, yet they have evolved very differently. Why this is so — and could Earth become like Venus — are questions still to be answered.

GALILEO

Galileo's six-year journey to Jupiter requires three gravity-assist flybys. The first two — one at Venus, one at Earth — were executed flawlessly. The Earth flyby in December 1990 inclined the spacecraft's orbit so that Galileo could rendezvous with the asteroid Gaspra in 1991.

The spacecraft camera's field of view for high-resolution images is tens of kilometers, but Gaspra's position was uncertain by far more than that. Controllers cut the uncertainty in half by referencing star images taken by the onboard camera; just four frames could be transmitted to Earth in time to alter the spacecraft trajectory and adjust camera pointing before the encounter. From 411 million kilometers away, mission navigators sent Galileo to within 1,600 kilometers of Gaspra — with such precision that the asteroid is at dead center in the images. Gaspra's irregular surface and odd shape show that it is an ancient traveler with a violent past. Galileo's instruments recorded information about Gaspra's surface composition and topography, atmospheric and magnetic field characteristics and ion and electron activity. Much of the data were stored aboard the spacecraft for playback when the high-gain antenna is operational or when the second Earth gravity-assist flyby occurs in December 1992.

When spacecraft controllers commanded Galileo's high-gain antenna to deploy in April, it did not open completely. Apparently, 3 of the 18 ribs failed to release, leaving them in tension at bowed-out positions. Controllers first attempted to unfurl the partially open antenna by "cold soaking" and next plan to try to free the ribs by conducting hot and cold cycling.

When Galileo reaches Jupiter in 1995, the spacecraft will release a probe into the Jovian atmosphere and then go into orbit to study the giant planet and its satellites. If the high-gain antenna is not available, two onboard low-gain antennas can be used for tracking, telemetry and command. Telemetry rates then would be about 10 bits per second, but intensive data compression and downlink performance could maximize the returns.

ULYSSES

Ulysses encounters Jupiter in February 1992, when Jovian gravity will bend the spacecraft's trajectory out of the plane of the ecliptic and send Ulysses into a five-year polar orbit about the Sun. The mission is a joint NASA and European Space Agency (ESA) effort to explore the Sun, the heliosphere above the solar poles, the heliospheric magnetic field, the solar wind and the Sun–wind interface.

During its two-week Jupiter flyby, Ulysses will search for gravity waves, measure the magnetosphere and observe the satellite Io's plasma torus, which stretches around Jupiter like a donut. The findings will supplement Jovian data acquired by the Voyager and Pioneer spacecraft during their earlier encounters.

Ulysses is steadily compiling data about the Sun and its corona. Scientists conducted radio experiments when the spacecraft was between Earth and the Sun and again when the Sun was between the

spacecraft and Earth. Ulysses observed heightened activity twice when the Sun produced many energetic particles influenced by a complex solar wind that included matter ejected from the corona.

Mission scientists were watching for the recurrence of a situation that can cause data loss. As Ulysses approached the Sun in November 1990, heating induced a wobbling motion (nutation) around the spacecraft's spin axis. Early in 1991, the solar-aspect angle again reached that same level — but this time there was no sign of nutation. Scientists anticipate that there may be other periods of solar heating; if it occurs, the antenna's scanning can be controlled to diminish the effects of any wobbling motion and reduce or eliminate data loss.

Interest in Ulysses' science results is already extremely high. Special Ulysses sessions were held by the European Geophysical Society in Wiesbaden, Germany, the Solar Wind 7 Conference in Goslar, Germany, and the Cosmic Ray Conference in Dublin, Ireland. A special session on Ulysses' Jupiter science is planned for the American Geophysical Union meeting in Montreal in May 1992.

JPL has sole tracking and data acquisition responsibility for Ulysses; the Laboratory also manages the U.S. experiments and shares the mission design and navigation roles with ESA.

TOPEX/POSEIDON

A mid-1992 launch aboard an Ariane rocket will place the Ocean Topography Experiment (TOPEX)/Poseidon satellite into orbit 1,336 kilometers above Earth's surface, where instruments will measure sea levels, chart variations in currents and monitor the effects of ocean circulation on global climate change. The mission is conducted by NASA and the French space agency (Centre Nationale d'Études Spatiales); the launch will be from the European Space Agency's facility in Kourou, French Guiana.

French and U.S. sensors were delivered to Fairchild Space and Defense Corporation, where workers completed spacecraft hardware fabrication and assembled the satellite in readiness for environmental testing before shipment to Kourou.

The satellite will rely on NASA's Tracking and Data Relay Satellite System and the Deep Space Network for command operations and data acquisition. To achieve precision tracking, a retroreflector on the satellite will return laser signals directed from the ground. Controllers will be able to pinpoint the satellite's position to within 13 centimeters, four times more precisely than Seasat's position was known 13 years ago.

A microwave radiometer will correct for atmospheric effects by measuring radiation from water vapor between the satellite and the ocean. The precision tracking will enable TOPEX/Poseidon to make accurate maps of sea-level changes, which represent sea-floor topography.

Thirty-eight principal investigators will study data gathered by TOPEX/Poseidon during the three years of its prime mission. Because the oceans are a key element in many global processes, findings will help assess global changes and improve weather forecasting and pollution control. The data should also prove valuable in monitoring the environmental conditions of offshore and coastal areas throughout the world.

MARS OBSERVER

A mission to study the surface, atmosphere and magnetic field of Mars will begin in September 1992 when a Titan III launch vehicle takes Mars Observer into Earth orbit. From there, a transfer orbit stage will boost the spacecraft on to an 11-month interplanetary cruise to the Red Planet.

Technicians have readied the spacecraft and instrument payload (a low-resolution line-scanning camera, a laser altimeter, spectrometers, magnetometers and an infrared radiometer) for final systems testing. The spacecraft was electrically integrated and the system-level test program begun; environmental and thermal/vacuum testing are scheduled for early 1992. Mission operations teams started preparations of ground data system hardware and software.

At its destination, Mars Observer will orbit the planet for a Martian year — 687 Earth days — gathering data on the planet's atmospheric composition and density, magnetic field and gravitational and surface characteristics. Near the end of its mapping endeavors in late 1995, Mars Observer will assist the Russian Mars '94 mission by relaying data from small penetrators and landed packages sent to the Martian surface by the Mars '94 spacecraft. The data will be radioed to the U.S. spacecraft, formatted on board by equipment supplied by the Centre Nationale d'Études Spatiales and transmitted to Earth by Mars Observer.

NASA and JPL have a cooperative arrangement with Russia on science experiments for the mission. JPL is responsible for the project management, mission design and mission operations of Mars Observer; General Electric's Astro-Space Division is building the spacecraft.

CRAF/CASSINI

The Comet Rendezvous Asteroid Flyby (CRAF)/Cassini project completed the second year of flight system development for Mariner Mark II, a new spacecraft planned for two missions: CRAF, which will fly by several asteroids and travel along with a comet towards the Sun, and Cassini, which will journey to Saturn and observe the planet and its rings, satellites and magnetosphere. NASA, the European Space Agency, the German space agency (Deutsche Agentur für Raumfahrtangelegenheiten) and the Italian space agency (Agenzia Spaziale Italiana) are cooperating in the dual missions.

Preliminary design reviews of the mission designs, spacecraft system and probe are complete and those for the engineering subsystems and the science instruments have begun. Reviews of the selected science investigations were conducted in anticipation of final confirmation by NASA in 1992.

In response to Congressional funding adjustments, the project has selected alternate scenarios for Cassini and CRAF. The Cassini launch aboard a Titan IV/Centaur is planned for October 1996 or 1997. Launch on either date places the spacecraft on a gravity-assist trajectory past Venus, Earth (twice if the 1996 launch is chosen), probably a small asteroid and Jupiter.

Both launch dates result in a Saturn arrival in June 2004 and a flyby of Phoebe, Saturn's outermost known satellite. Cassini will swoop through a gap in Saturn's famous rings and acquire close-encounter science data, perform an orbit-insertion maneuver and recross the rings in the same gap at a different location on the outbound trajectory. The accompanying Huygens Probe — named for the Dutch astronomer who discovered Titan — will separate from the

TECHNICIANS READY THE MARS OBSERVER PRESSURE MODULATOR INFRARED RADIOMETER FOR TESTING. THE INSTRUMENT WILL MONITOR ATMOSPHERIC PRESSURE, WATER VAPOR, TEMPERATURE, POLAR RADIATION AND ENERGY BALANCE.

GALILEO'S FLIGHT TEAM COORDINATED WITH MISSION CONTROL AND THE DEEP SPACE NETWORK FOR THE ENCOUNTER WITH GASPRA. DURING CLOSEST APPROACH, GALILEO WAS ONLY 1.5 SECONDS AND 5 KILOMETERS FROM ITS AIM POINT.

spacecraft during the first orbit and descend 22 days later on a three-hour journey through the atmosphere of Titan to its surface. Cassini will continue with a four-year, detailed study of Saturn and its major satellites.

The CRAF mission has also changed, from a February 1996 launch and a 2003 rendezvous with comet Tempel 2, to an April 1997 launch and a rendezvous with comet Kopff in 2006. The trajectory will require gravity assists at Mars in 1998 and at Earth in 2000 and 2003; the spacecraft will observe three asteroids on the way to comet Kopff. Rendezvous with comet Kopff will begin three years before perihelion, allowing for lengthy observations as the comet nears the Sun.

The European Space Agency has completed preliminary design reviews on all six instruments selected for the Huygens Probe and subcontractors have been selected. The Deutsche Agentur für Raumfahrtangelegenheiten is providing the Cassini Cosmic Dust Analyzer, the CRAF Cometary Matter Analyzer and much of the CRAF propulsion module. The Agenzia Spaziale Italiana will supply the high-gain antenna and the visible wavelength portion of the Visible/Infrared Mapping Spectrometer for both missions, plus portions of the S-band and Ka-band radio science communications equipment and about half of the orbiter's radar for Cassini.

JPL plans to retain X-band command capability for the missions, but the spacecraft will also carry Ka-band uplink equipment. By the time Cassini reaches Saturn, the Deep Space Network will be able to operate at Ka-band, taking advantage of the higher frequency's greater data capacity and reduced transmission power.

VOYAGER

Years after their extraordinary planetary encounters, the two Voyager spacecraft continue to return data as they head toward the outer boundaries of the solar system in search of the heliopause — the region where the Sun's influence diminishes and the beginning of interstellar space can be sensed. The spacecraft will first encounter a termination shock that signals an abrupt slowing in the solar wind. The exact location of the heliopause is unknown, but astronomers believe that it is about 11 billion to 22.4 billion kilometers from the Sun; the spacecraft may reach the termination shock by the end of the century.

Each Voyager's complement of six instruments collects and continuously transmits field, particle and wave data that are periodically tracked by the Deep Space Network. The spacecraft are also engaged in ultraviolet astronomy studies of active galaxies, quasars and white dwarf stars. Astronomers can make simultaneous observations with Voyager instruments and ground-based telescopes.

Voyager 1 is speeding along a 35-degree heading above the plane of the ecliptic and is approximately 7 billion kilometers from the Sun. Voyager 2, traveling below the ecliptic plane along a 48-degree heading, is about 5.4 billion kilometers from the Sun. Both Voyagers are traveling away from the Sun at a rate of some 448 million kilometers per year.

MESUR

JPL was given lead responsibility for NASA's Mars Environmental Survey (MESUR), which will place 16 small landers on the surface of Mars later in the 1990s. The mission will send four of the instrumented landers on each of four launches. The landers will be distributed globally to study the atmosphere, surface and interior of the planet.

FLIGHT PROJECTS SUPPORT

JPL has expanded its multimission concept for flight projects support and further improved its abilities to manage concurrent activities. Previously, each flight project built and operated its own ground system; now, the Flight Projects Support Office (FPSO) provides substantial portions of shared systems.

During 1991, FPSO extended its multimission telemetry system to the Voyager, Mars Observer and Ulysses projects while maintaining services to the Magellan project. The Multimission Control Team and the Data Systems Operations Team support several projects. A multimission navigation environment was created with networked workstations, which improved responsiveness and cut expenses by reducing the use of mainframe computers. The Laboratory also enhanced productivity through its Technology Initiatives program by implementing tasks designed to lower costs and improve efficiency, such as shifting the burden of routine mission planning to "intelligent" software.

Navigation Ancillary Information Facility

The Laboratory's Navigation Ancillary Information Facility (NAIF) supplies JPL flight projects with data, software and standards for reconstructing the observation geometry of spacecraft instruments. NAIF's products are used to plan space science observations and determine parameters that affect the interpretation of images, spectra, particle counts or other space science instrument output.

Scientists on several spacecraft programs made use of NAIF this year. The Galileo team was aided in analyzing data from flybys of Earth and the asteroid Gaspra; the Mars Observer group was assisted with science training, and Cassini scientists were helped in their evaluation of the proposed Saturn system tour. Scientists at the Space Telescope Science Institute successfully applied NAIF's moving-object support capability in planning the first observations of planets and comets by the Hubble Space Telescope. Other investigators employed the facility's data and software to plan observations and to further analyze data from the Voyager spacecraft.

NAIF's standards and products sparked continued interest among NASA's international partners. Russian specialists are committed to using the facility in supporting their Mars '94/'96 program and their French and German partners have begun familiarizing themselves with the capabilities of the more than 600 modules in NAIF's software library.

Knowledge Systems

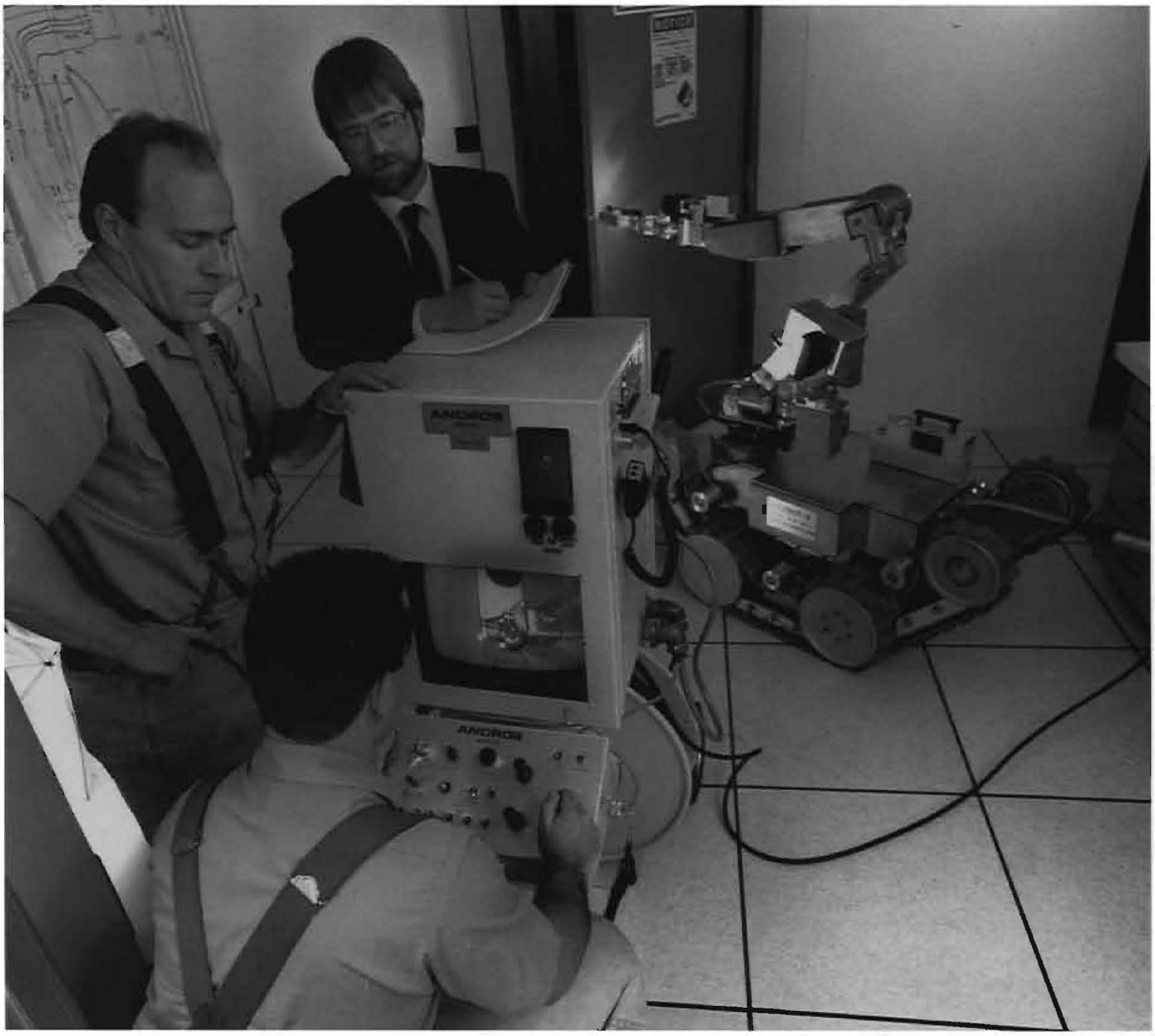
Artificial intelligence and computer science techniques are being used to ensure spacecraft health, manage increased amounts of science data and relieve operations workloads. JPL has successfully used several types of artificial intelligence — knowledge systems — to capture human problem-solving abilities.

The Spacecraft Health Automated Reasoning Prototype (SHARP) was installed in the JPL Space Flight Operations Center to assist mission operators in analyzing the health and status of spacecraft and ground systems. Controllers are evaluating SHARP in Magellan operations and will use it to monitor Galileo's power subsystem. One version of the prototype demonstrated the ability to simplify the calibration and configuration of spacecraft tracking. A derivative system for monitoring and controlling telecommunications links is being readied for testing at the Goldstone Deep Space Communications Complex.

GALILEO PERSONNEL EVALUATE THE SPACECRAFT'S ENCOUNTER WITH GASPRA. INSET: AN IMAGE OF THE ASTEROID TAKEN AT 16,200 KILOMETERS. THE FINAL MOSAIC OF IMAGES WAS COMPLETED WITHIN 10 MINUTES OF CLOSEST APPROACH.

The Laboratory's efforts *focus on basic research and* the development of instruments and techniques for space exploration and the study of Earth and its environment. These activities make essential contributions to the *advancement of knowledge* about the planets, solar physics and astronomy; studies of our own planet and the processes that change it may even prove to be critical to human survival. Each year's progress answers more questions and *generates substantial quantities of data* to process, analyze, archive and make available to scientists, educators and the public. Work in 1991 provided new information about the nature of asteroids, the surfaces of Venus, Mercury and Earth, the Sun's radiation and the effects of industrial and natural chemicals *on Earth's fragile ozone layer* Various types of radar were used to track asteroids, observe other planets and measure global changes *from satellites and aircraft*. Experiments were carried out to compile data on climate and atmospheric chemical composition. The Laboratory continues to develop scientific visualization techniques that combine and present data sets *in graphic displays* for analysis and education.

THIS AUTOMATED ARCHIVAL SYSTEM FOR THE CRAY Y-MP2E/116 SUPERCOMPUTER CURRENTLY HOLDS MORE THAN 3,000 TAPE CARTRIDGES THAT STORE USER DATA FOR A WIDE RANGE OF SCIENTIFIC DISCIPLINES.



UNDER REMOTE COMMAND, HAZBOT II PERFORMS IN A SIMULATED HAZARDOUS SITUATION. JPL'S AUTOMATION AND ROBOTICS TECHNOLOGIES HAVE BEEN CRUCIAL TO THE SUCCESS OF AUTOMATED SPACE MISSIONS.

Asteroid Radar Echoes

Astronomers from JPL, Arecibo Observatory, Cornell, Harvard and Washington State University have been observing near-Earth asteroid 1986 DA since its discovery five years ago. The analyses of radar return data, completed just this year, show that tiny 1986 DA has an irregular, possibly bifurcated shape and a smooth surface. Its radar reflectivity is much higher than other radar-detected asteroids and is about 10 times the lunar value. Appearing to be metal-rich, with a surface that is blanketed by a porous regolith no more than a few centimeters deep, 1986 DA is probably a fragment of a larger asteroid that melted, differentiated, cooled and subsequently was shattered in a catastrophic collision.

Meteoritic metal is primarily iron with some nickel, but it also contains concentrations of gold (perhaps one part per million) and platinum-group elements (around 10 parts per million). If these abundances apply to 1986 DA, it would contain some 10 billion kilograms of iron, a billion kilograms of nickel, 100 million kilograms of platinum-group metals and 10 million kilograms of gold.

Solar System Radar

Radar astronomers at Caltech and JPL mapped the entire visible disk of Mercury for the first time without north and south ambiguities by combining the capabilities of the Deep Space Network (DSN) with those of the National Radio Astronomy Observatory's Very Large Array (VLA) of antennas. Returns from an 8.51-gigahertz radar signal transmitted from the Goldstone, California, 70-meter antenna were received by the array of twenty-seven 25-meter antennas in Socorro, New Mexico. Researchers observed a striking feature: a very bright elliptical patch, possibly ice, near Mercury's north pole.

Mercury was mapped again when it had rotated by 101 degrees of longitude, and some returns were compared with photographs taken by Mariner 10 in the early 1970s. Large, bright areas around the Rodin, Monet and Kuiper craters suggest the presence of ejecta blankets, while the dark crater floors indicate smooth features, probably congealed lava. On the side of Mercury not photographed by Mariner 10, radar imagery shows broad, bright features where enhanced sodium and potassium spectral lines have been recorded by ground-based observatories, suggesting the presence of a tenuous atmosphere.

In a repeat of a previous success, Saturn's largest moon, Titan, was observed with 4-centimeter radar using the Goldstone 70-meter antenna and the VLA. The resulting data, which are needed to plan details of the Cassini Titan radar experiment, support the belief that Titan's rotation is not locked to Saturn.

The recently discovered near-Earth asteroid 1991 JX was observed at about 5.7 million kilometers, beginning the first ranging observing tracks with a refurbished high-power transmitter. Goldstone and VLA antennas also observed newly discovered near-Earth asteroid 1991 EE and main-belt asteroid Bamberga. Goldstone radar alone observed two asteroids — near-Earth 1982 BB and main-belt Iris — in another demonstration of the DSN's role in JPL's expanding asteroid science effort. Radar measurements provide excellent asteroid orbital data, allowing the objects to be tracked for many years.

Measuring Planetary Relativistic Deflection

An analysis of three-year-old data from DSN antennas in California and Australia confirmed the first detection of relativistic deflection of radio waves by a planet. In 1988, the ray path of the extragalactic radio source P 0201+113 passed within 200 arcseconds of Jupiter. By using Very Long Baseline Interferometry techniques with two DSN antennas, scientists determined the apparent angular shift of the radio source's signals due to the giant planet's gravitational field. The first position measurements were compared to data taken about 13 days later when the ray path was far from Jupiter. The analysis, which was just completed this year, showed an average 300-microarcsecond difference between the two angular positions due to Jupiter's influence. The result agrees with the predictions of Einstein's theory of general relativity.

The experiment demonstrated a radio tracking capability with 160-microarcsecond accuracy, which projects to a plane-of-sky distance accuracy of about 500 meters at Jupiter. This capability will improve the determination of spacecraft arrival time, probe release angle and the location of imaged objects in an inertial reference frame for such outer-planet missions as Galileo and Cassini.

Rovers

Mobility is an essential element for surface investigations. During 1991, JPL emphasized the development of miniature unpiloted vehicles, simplified control systems for operation on planetary surfaces and instruments and subsystems for identifying and gathering samples.

Rocky III weighs about 20 kilograms and is powered by lead–acid gel cells, with a control system that comprises sensors and actuators closely coupled through machine intelligence–based software. The software, derived from an approach developed at JPL and the Massachusetts Institute of Technology, uses hierarchies of simple behaviors that enable the rover to respond to events reflexively. Rocky III was tested on rugged terrain that is similar to the Viking 2 Martian landing site and acquired samples using a manipulator and camera from locations chosen by human operators.

Go-For is even smaller than Rocky III and weighs just 4 kilograms. Go-For is steered by differential action of the left and right wheels; its front and back wheels are attached to independently controllable struts for navigational flexibility and self-righting capability. During a planetary surface exploration, a human operator at a ground-control station would observe Go-For's activities and send routing and task instructions to a lander for relay to the rover.

In other progress, algorithmic and hardware modifications further improved the performance of Robby, a 1,000-kilogram, self-contained, self-guided rover test bed; its speed over rough natural terrain increased from 25 to 80 meters per hour. JPL also applied rover technology to Hazbot, designed to help JPL emergency teams respond to dangerous situations such as chemical spills. During tests, Hazbot entered a building, positioned sensors and unlocked and entered a storeroom where it detected and localized spilled chemicals.

Microinstruments

A new generation of instruments with dramatically reduced mass and volume, the products of microelectronic principles developed at JPL, will soon make possible space and Earth science missions that

were previously considered impractical. These instruments may be added to the rovers to provide geoscience and weather information on the surface of Mars.

EARTH SCIENCE

Microwave Limb Sounder

After a decade of balloon and aircraft experiments, the Microwave Limb Sounder (MLS) was launched by the Space Shuttle Discovery in September aboard NASA's Upper Atmosphere Research Satellite. The MLS is the first spaceborne instrument to collect near-global stratospheric data on chlorine monoxide — a key contributor to ozone depletion. Data collected by MLS will help scientists understand the processes that affect the ozone layer.

Less than a week after launch, MLS produced maps showing the enhanced presence of chlorine monoxide in the Arctic ozone hole. The instrument also measures ozone, water vapor, temperature and sulfur dioxide injected into the stratosphere by volcanic eruptions. MLS measurements are not affected by volcanic aerosols, and it was able to detect low concentrations of ozone in the tropics within the aerosols generated by the erupting Mt. Pinatubo volcano in the Philippines.

Collaborating with JPL on the experiment are research groups in the United Kingdom at Heriot–Watt University, Edinburgh University and Rutherford Appleton Laboratory. An advanced version of the Microwave Limb Sounder is planned for launch in 2002 as part of NASA's Earth Observing System program.

Alaska Radar Processing Facility

In August, the Alaska Synthetic Aperture Radar Facility in Fairbanks — designed and built by JPL for NASA and operated by the University of Alaska — began gathering and processing radar data from the European Space Agency's Remote Sensing Satellite (ERS–1).

The first radar images from ERS–1's passes over the Canadian Arctic showed mountains, valley glaciers, river valleys, tundra lakes, highways, wind roughening over open water, internal waves, pack ice and angular ice floes. The satellite's radar can image significant contrast among prominent sea-ice types. Studies of sea-ice geophysical products are valuable as indicators of heat flux in the polar oceans and possible feedbacks to global warming.

Greenland Ice Sheet Experiment

In June, a NASA DC-8 aircraft equipped with JPL's multipolarization Airborne Synthetic Aperture Radar (AIRSAR) flew over the Greenland ice sheet to examine patterns of surface snow accumulation and melting. The effort was organized by JPL scientists to coincide with surface experiments by American, Danish, German and Swiss researchers and data collection flights by NASA's P3 aircraft from the Wallops Flight Facility.

The researchers' objective is to establish an elevation baseline for the Greenland ice sheet. They plan to study the effects of climatic change over periods exceeding 10 years on patterns of seasonal snow accumulation and ice ablation. Future research using high spatial resolution radar data gathered by ERS–1 will extend this hydrologic monitoring activity and provide information on the stability of Earth's large ice sheets in response to global climatic changes.

Atmospheric Modeling With Supercomputers

Laboratory scientists used a climate model of moderate size and complexity to assess three computer architectures for handling global climate simulations at varying resolutions. Performances were comparable at moderate resolutions, but for problems requiring increased resolution, the two systems using parallel architecture were found to be more effective because of their superior scaling properties.

JPL scientists are developing a new data-assimilation scheme — a statistical process for incorporating observations of atmospheric and oceanic variables such as temperature and wind into a general circulation model — to run on one of the computers. Data assimilation is an essential tool in meteorology and oceanography because it offers a statistical estimate of the state of the atmosphere–ocean system over specific periods. Increases in the spatial and temporal densities of data from high-resolution Earth-orbiting instruments will require improved assimilation algorithms. Innovations in the JPL data-assimilation approach provide estimates on the order of one million variables in describing the state of the atmosphere at any time. The approach requires factors of thousands more numerical operations than are required by traditional data-assimilation methods.

European Remote-Sensing Campaign

Two JPL instruments — the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and the Airborne Synthetic Aperture Radar (AIRSAR) — played key roles in a six-week airborne remote-sensing campaign conducted by NASA and European scientists. AVIRIS acquires images in 224 narrow spectral bands across the solar-reflected portion of the spectrum. The radar, a fully polarimetric, multifrequency imaging sensor, acquires data in C-, L- and P-bands. It also has an interferometric mode for data collection that is used in topographic mapping of Earth's surface.

AVIRIS was flown aboard a high-altitude ER-2 aircraft over continental Europe for studies of energy and evaporation fluxes in Germany, hydrological processes in Italy, vegetation characteristics in France and the Netherlands and desertification processes in Spain. An experiment by JPL and European scientists in southern France validated the instrument's spectral and radiometric calibration during the European campaign, which generated more than 65,000 square kilometers of spectrometric imagery.

In flights on a DC-8 aircraft from the NASA Ames Research Center, SAR imagery was obtained over European countries, Greenland, Iceland, off the coast of Norway and over the Mediterranean Sea. The goals were to characterize radar responses of forests for inferring biomass and other structural properties, to map surface geology at volcanic and desert sites and to investigate ocean-circulation patterns and surface wave–current interactions. The campaign also aided in cross-calibrating airborne and spaceborne radars. During 175 hours of flight, the sensor obtained more than 300,000 square kilometers of radar imagery.

The data collected by the two JPL sensors will be studied by investigators from JPL, other NASA centers, U.S. universities and their European counterparts in addressing a wide range of issues related to global change processes and the Earth sciences in Europe.

A QUALITY ASSURANCE INSPECTOR AND A FABRICATION ENGINEER REVIEW THE NASA SCATTEROMETER (NSCAT) DATA SUBSYSTEM'S ELECTRONIC CHASSIS. NSCAT WILL FLY ABOARD A JAPANESE SATELLITE TO MEASURE WINDS OVER THE OCEANS.

THE MICROWAVE LIMB SOUNDER (MLS), LAUNCHED ABOARD NASA'S UPPER ATMOSPHERE RESEARCH SATELLITE. ONE OF 10 INSTRUMENTS ON THE SATELLITE, MLS IS COLLECTING DATA ON OZONE DEPLETION IN THE STRATOSPHERE.

Spaceborne Imaging Radar

The Laboratory plans to fly a multiple-frequency Synthetic Aperture Radar called SIR-C/X-SAR on three space shuttle missions starting in 1993. The radar combines advanced sensors from JPL, the German Federal Ministry for Research and Technology and the Italian space agency. The shuttle flights are part of NASA's Spaceborne Imaging Radar program. Data gathered by a prototype sensor during 1991 flights over the U.S. and Europe are being used to develop biogeophysical algorithms that will be verified during the future missions.

During the flights, data on the carbon cycle — the movement of carbon from the atmosphere to plants to animals and then back to the atmosphere — will be collected from the Amazon basin, northern Michigan, southern Germany and agricultural regions in the Netherlands. Data on the hydrologic cycle — the evaporation of moisture from the oceans, its transport through the clouds, its precipitation over land and subsequent return through runoff to the sea — will be gathered from Brazil, Italy and the midwestern United States. Paleoclimatic and geological studies will focus on North Africa, the southwestern United States and northwestern China; oceanography experiments will be conducted over the south and north Atlantic. Radar technology experiments will also be performed to enhance the capabilities of future sensors designed for monitoring global change.

Atmospheric Infrared Sounder

NASA's Earth Observing System program will study Earth's environment and the effects of increased greenhouse gases on climate. NASA has placed primary emphasis on studies of cloud radiation and the global water cycle, with the JPL Atmospheric Infrared Sounder (AIRS) designated as lead instrument for observation of the thermal structure and distribution of water vapor in the atmosphere. Water vapor is the most active greenhouse gas in Earth's environment; it surpasses carbon dioxide in this respect.

Through its multispectral coverage (3.4 to 15.4 micrometers) and its high spectral resolution, AIRS can provide information on a wide range of climatic parameters, including clouds, total ozone levels, snow and ice-cover distribution and ocean-surface temperature. Some parameters, such as land-surface temperature and emissivity, will be measured for the first time. These data will help determine the effects of increased greenhouse gases and reduce uncertainty in predicting climate changes. The instrument's sensitive mercury–cadmium–telluride detector arrays, which are cooled to 60 kelvin, are the key to accurate measurements. The AIRS project achieved a breakthrough in 1991 with engineering model demonstrations of the performance of the cryogenic coolers with their required long life and low vibration.

AIRS will contribute to improving forecasts when it flies aboard the National Oceanic and Atmospheric Administration's weather satellite. The atmospheric temperature profiles that AIRS is expected to provide to the National Weather Service will be twice as accurate as those derived from the current system, making weather forecasts substantially more accurate and extending their range up to a week or longer.

Measuring Earth Rotation With the Global Positioning System

For missions later in this decade and beyond, continuous and near-real-time data about variations in Earth orientation will be required so that the uncertainty about the coordinates of NASA's Deep Space Network can be reduced to less than 3 centimeters. This is equivalent to making an angular measurement of a given location on Earth with an accuracy of a few parts in one billion. JPL proposed and successfully demonstrated an approach using the Global Positioning System navigation satellites rather than large antennas.

Because the satellites move in very stable high-Earth orbits, it is possible to determine small variations in Earth's axis and rate of rotation. Precise measurement of these variations is critical for the calibration of deep space tracking data. A three-week experiment confirmed theoretical calculations about the navigation satellites' sensitivity to Earth orientation. A record of changes in Earth rotation over the three-week period showed that the Global Positioning System measurements can detect deviations as small as 0.1 millisecond, which corresponds to a position change of about 4 centimeters at the tracking sites. These figures not only agree with large-antenna Very Long Baseline Interferometry measurements but provide twice the time resolution.

ASTROPHYSICS AND SPACE PHYSICS

Stellar Interferometry

JPL, the Naval Research Laboratory and the U.S. Naval Observatory collaborate on observations using the Mark III stellar interferometer at Mt. Wilson in the San Gabriel Mountains. The Mark III offers high angular resolution, laser-monitored delay lines and other advanced features. It also serves as a prototype for interferometers such as the one planned for the Keck Observatory on Mauna Kea in Hawaii and for space-based instruments such as the Orbiting Stellar Interferometer, a JPL-developed flight project concept.

In astrometric measurements using the Mark III, observations over five nights of a wide-angle set of 12 stars yielded formal errors of 6 milliarcseconds in declination and 9 milliarcseconds in right ascension. These accuracies are significantly better than those of conventional astrometric catalogs, which quote formal errors of 50 milliarcseconds.

JPL scientists are using the Mt. Wilson stellar interferometer along with spectroscopic and photometric measurements to determine the fundamental physical parameters of binary stars, including mass, luminosity, color and distance. Two binary stars — β Arietis, initially observed with spectroscopy, and θ^2 Taurus, the brightest double star system in the Hyades cluster — were resolved with the Mark III. Interferometry and spectroscopy provided a direct measure of the distance to the Hyades, an important measurement in calibrating cosmic-distance metrics.

Stellar-diameter measurements by Navy scientists using the Mark III yielded accuracies of 1 percent for 12 stars with stellar diameters larger than 4 milliarcseconds and 3 percent or better for 70 stars. These accuracies are high enough to provide constraints on theories of stellar formation and evolution.

Soft X-Ray Telescope

Hidden details and structures in the solar corona are rendered visible by X-ray imagery. To help reveal the nature of the Sun and its corona, the Soft X-Ray Telescope on the Yohkoh satellite, which was launched from Kagoshima Space Center in Japan in August, is collecting coronal images at the rate of one every two seconds. The telescope's camera was developed by JPL for the cooperative mission by Japan, the United Kingdom and the United States. The telescope itself is a joint experiment between the National Astronomical Observatory of Japan and NASA.

Soft X-rays, which are quite weak and do not penetrate Earth's atmosphere, are generated when temperatures of the corona's gases exceed 1 million degrees Celsius. These coronal temperatures are 10 to 30 times higher when a solar flare is active. The telescope's mirror focuses incoming X-rays on a charge-coupled-device array and the detector then converts photons to digital electrical signals, which can be used to determine photon energy and infer the coronal temperature. Hundreds of images have already been obtained; the new data can help answer some of the many questions about the Sun, such as why the corona is so much hotter than the surface.

The NASA Marshall Space Flight Center manages the U.S. portion of the Yohkoh mission. Japan's scientific space program is managed by that nation's Institute for Space and Aeronautical Sciences.

Solar Total Irradiance Monitoring Program

JPL is conducting a series of experiments to compile a long-term, high-precision database on the variability of total solar irradiance — the total energy supplied to Earth by the Sun — that will aid our understanding of the relationship between solar variability and Earth's climate system. Since our atmosphere absorbs much of the energy coming from the Sun, measurements must be made from a satellite.

The first Active Cavity Radiometer Irradiance Monitor (ACRIM I) was part of NASA's Solar Maximum Mission (1980–1989). ACRIM I detected a variability of 0.1 percent in phase with two solar activity cycles, demonstrating a positive relationship between total irradiance and solar activity — the missing link in the correlation of past climatic changes with depressed levels of solar-magnetic activity. Models indicate that trends in the total irradiance of as little as 0.5 percent per century could eventually produce the entire range of climate extremes known to have existed in the past.

Accumulating a database capable of revealing subtle solar trends requires many long-duration experiments related to each other at a high level of precision. The satellite instrumentation does not have high enough accuracy to sustain the necessary precision, but an "overlap" strategy that compares successive experiments in flight can provide an acceptable relative precision. The Challenger disaster delayed the launch of ACRIM II on the Upper Atmosphere Research Satellite until 1991; thus, the overlap strategy could not be implemented for ACRIM I and II. Their data can be related with useful precision by employing a strategy that utilizes the coincident total irradiance data from the Earth Radiation Budget experiment aboard the Nimbus 7 satellite to create a statistically leveraged link between ACRIM I and II.

NASA has principal responsibility for the work in its role as the lead agency for the Solar and Earth Radiation portion of the National Climate Program. Additional ACRIM deployments are planned for flights of opportunity during the 1995–2015 period as part of NASA's Earth Observing System program.

Orbiting Astrophysics Instruments

The Laboratory is NASA's lead center for the Space Infrared Telescope Facility (SIRTF), an Earth-orbiting observatory that will make observations from an altitude of 100,000 kilometers. The telescope's infrared measurements will supplement astrophysical studies at various wavelengths by NASA's other great space-based observatories: the Hubble Space Telescope, the Compton Gamma Ray Observatory launched in April and the Advanced X-Ray Astrophysics Facility to be launched in 1999.

JPL and three university-based instrument teams have been working on detector arrays for SIRTF's three focal planes. The arrays will incorporate hundreds of thousands of individual detectors, each a thousand times more sensitive than the elements on the 1983 Infrared Astronomical Satellite. The arrays will provide response over the entire infrared spectral range and will be used for both imaging and spectroscopy.

The Laboratory is considering two possibilities for other astrophysics studies. The Submillimeter Intermediate Mission would perform a spectral-line survey of astrophysical objects at submillimeter wavebands from a highly elliptical Earth orbit to further our understanding of the structure and evolution of galaxies. The Orbiting Stellar Interferometer would use space-based interferometric techniques to search for answers to fundamental questions about the size and age of the universe, the mass and structure of our galaxy and the existence of black holes.

Wide Field/Planetary Camera 2

The first servicing mission to the Hubble Space Telescope is planned for November 1993, when astronauts will substitute the Wide Field/Planetary Camera 2 (WF/PC 2) for the original instrument that was launched with the telescope in 1990. The WF/PC 2 was redefined as the problems posed by the aberration in Hubble's primary mirror became better understood. The redesigned unit will contain fewer camera heads than the original, but will have greater alignment capabilities because of added mechanisms that allow inflight adjustment of its optical system. The WF/PC 2 should be able to correct for essentially all the distortion from the primary mirror.

A new type of charge-coupled device (CCD) imaging sensor was chosen for WF/PC 2. The new CCDs are expected to perform better than those in the current WF/PC, having better uniformity, noise performance and dynamic range characteristics. Prototype devices were delivered to the Laboratory at year's end and early tests confirmed virtually all anticipated performance improvements.

The current WF/PC performed flawlessly through 1991. Responsibility for the instrument has been shifted from Caltech/JPL to the Hubble Space Telescope Science Institute in Baltimore, Maryland.

Aspherical Supernova Explosion

During the year, astronomers from the Harvard–Smithsonian Center for Astrophysics and other institutions reported the capture of time-lapse images of the most luminous supernova explosion ever seen. Instead of a smooth, spherical expansion of gas, scientists noted three protrusions, indicating a fragmentation of the shock front.

The observations were a consequence of the periodic coordination of radio observations by astronomers around the world who form cooperative, high-resolution radio telescope systems. NASA's Deep Space Network participates in these efforts by reserving time on its 70-meter antennas for these Very Long Baseline Interferometry observations. The configurations for the Harvard–Smithsonian observations included the 70-meter antennas at Goldstone, California, and Madrid, Spain.

INFORMATION SYSTEMS

Scientific Visualization

Several activities at JPL are developing software for interactive analysis and visualization of multidimensional, multivariate data and imagery. This interactive analysis capability for handling large, complex data sets is expected to be applicable to different computing environments and compatible with low-cost workstations. The dramatic animations produced by scientific visualization techniques have already proven their value in science and education.

To manage the demands that interactive scientific visualization imposes on computer graphics performance, JPL scientists developed the Linked Windows Interactive Data System. The system links data displays with controls for manipulation by an analyst, providing flexible, rapid interaction with complex data to detect trends and anomalies and make correlations. The system has been tested with atmospheric, oceanographic and geologic data sets and has been applied to the analysis of atmospheric ozone measurements by the Upper Atmosphere Research Satellite.

During 1991, the Laboratory continued to demonstrate its skills in presenting data through animation. "Monterey: The Bay," cosponsored by NASA and the Navy and released in March, combines seven sets of geophysical data obtained from satellites, field investigations and modeling. "Blue Planet," an IMAX movie released worldwide, includes JPL's full-resolution, three-dimensional perspective animation of a computer-simulated flight along the San Andreas Fault from the Salton Sea to San Francisco. The film also features a 20-second simulation of a large earthquake with an epicenter on the San Andreas just south of San Francisco Bay.

In the Solar System Visualization project, scientists are applying visual analytical tools to planetary investigations. Their goals are to reexplore the planets using NASA mission data and create new tools, technologies and materials for science, education and the public. Science video products and perspective maps for every planet have been produced, and visualizations have been featured on the covers of *Science*, *Scientific American* and *U.S. News and World Report.*

Planetary Data System

During its first year of operation, the Planetary Data System responded to more than 3,000 orders from planetary scientists totaling some 6,000 gigabytes of data — more than the combined total previously distributed from all planetary missions. Data were disseminated in several media, including computer tape and compact disk read-only memory (CD-ROM). CD-ROM technology, a spin-off from the familiar audio CD, offers a compact, durable medium for storing large quantities of data.

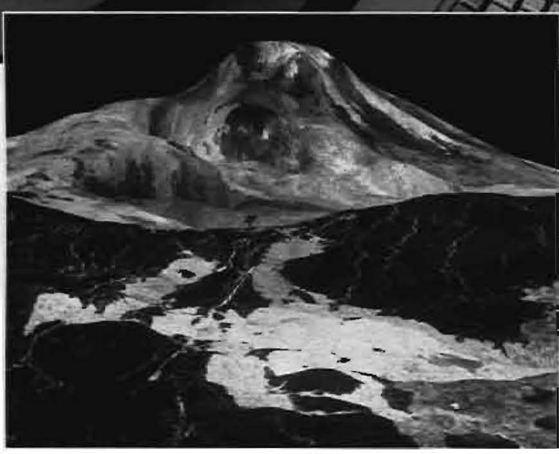
The Planetary Data System restored and published 15 new CD-ROMs from the Voyager 2 Neptune encounter, the Viking mission and the Geological Remote Sensing Field Experiment. In addition, the first released science data from the Magellan project were archived and distributed. The staff also investigated compact disk write-once technology, which allows CDs to be written at the Laboratory without sending the data to vendors for mastering and copying, as must be done with CD-ROMs. Write-once CDs have proven useful for temporary storage or as proof copies before committing to large-scale duplication of CD-ROMs.

Data, information about archiving standards and in-depth scientific expertise are made available to a broad planetary science community through eight distributed teams of scientists and engineers. The teams represent more than 20 U.S. universities and cover planetary rings, plasma interactions, imaging, geosciences, planetary small bodies and navigation information. Planetary archive products are available from the Planetary Data System or the Space Science Data Center at the NASA Goddard Space Flight Center.

Delta Supercomputer

Scientists and engineers began using the Intel Touchstone Delta supercomputer, installed at Caltech in May, to solve complex problems in global climate modeling, nuclear waste cleanup and determination of the structures of viruses. The Delta, which set a world performance record in standard benchmark tests, is used for the Concurrent Supercomputing Consortium, an alliance of 14 institutions and agencies, including NASA, Caltech and JPL.

JPL researchers plan to use the Delta with a new approach for combining multiple data sets for the interactive exploration of three-dimensional geophysical data. The supercomputer will also help analyze Magellan radar images of Venus and produce films for data visualization.



TECHNICIANS AT THE IMAGING ANALYSIS SYSTEMS LABORATORY EXTRACT INFORMATION FROM IMAGE DATA. INSET: THIS VIEW OF VENUS IS GENERATED FROM MAGELLAN DATA. THE VOLCANO'S HEIGHT IS EXAGGERATED TO REVEAL GEOLOGICAL FEATURES.

During 1991, NASA's *Deep Space Network* (DSN) supported some 27 prime and extended deep space and near-Earth missions, including Ulysses, Galileo, Magellan, Voyagers 1 and 2, Pioneers 10, 11 and 12, the International Cometary Explorer, Nimbus, the European Hipparcos and the space shuttle. *Launch and early orbit* support were provided for Tracking and Data Relay Satellite–E, the Compton Gamma Ray Observatory and the Upper Atmosphere Research Satellite. *Navigation support was provided* to Japan's Hiten satellite and Yohkoh spacecraft. Also, a simplified telemetry data recording capability was initiated *that will make it easier* for the DSN to employ other nations' or agencies' antennas during temporary overload conditions. A series of Very Long Baseline Interferometry experiments was begun using three Soviet antennas and the DSN's 70-meter antenna near Madrid, Spain, *to establish a reference frame* between the two networks for cooperative tracking of the U.S. Mars Observer–Russian Mars '94 and the Russian Radioastron missions. Finally, negotiations progressed *for telemetry acquisition* from the two Voyager spacecraft with Russia's two 70-meter antennas.

THE 34-METER BEAM-WAVEGUIDE ANTENNA AT GOLDSTONE WILL SIGNIFICANTLY ENHANCE THE EFFICIENCY OF DEEP SPACE MISSION SUPPORT. THE ANTENNA IS A PROOF MODEL FOR OTHERS THAT WILL BE BUILT AT CANBERRA, AUSTRALIA, AND MADRID, SPAIN.

A BEAM-WAVEGUIDE TEST FACILITY IN THIS ANECHOIC CHAMBER CHARACTERIZES ELEMENTS FOR THE GOLDSTONE 34-METER ANTENNA. THE BEAM-WAVEGUIDE DESIGN REMOVES ALL ELECTRONICS FROM THE EXPOSED ANTENNA DISH.

DSN OVERVIEW

The Deep Space Network (DSN), NASA's worldwide system for communicating with spacecraft above low Earth orbit (above 10,000 to 15,000 kilometers), is managed by JPL through the Telecommunications and Data Acquisition Office. The DSN tracks satellites not visible to NASA's geosynchronous Tracking and Data Relay Satellite System and supports other NASA missions. It also assists foreign space agencies on a reimbursable or cooperative basis. The DSN's 26-meter antennas are used for near-Earth operations; its 34- and 70-meter antenna subnetworks provide deep space support.

The DSN's three Deep Space Communications Complexes — at Goldstone in Southern California's Mojave Desert, near Madrid, Spain, and near Canberra, Australia — are separated by approximately 120 degrees of longitude so that a distant spacecraft is normally in view of one of the stations. The Network Operations Control Center at JPL directs the operations of each complex; a spacecraft compatibility test facility at JPL and a launch support facility at the NASA Kennedy Space Center in Florida are also part of the DSN.

JPL manages various space telecommunications activities for NASA, including a spacecraft radio development program, a space frequency management activity and a development and demonstration program in ground-based deep space communications and radio navigation. The Laboratory participates in NASA's Search for Extraterrestrial Intelligence project, manages the Goldstone Solar System Radar and engages in radio science and radio astronomy studies.

Spacecraft communications and radio navigation present daunting challenges. Signal degradation for the Voyager spacecraft, more than 5 billion kilometers away, is 20 billion times greater than that of a satellite 36,000 kilometers above Earth's equator. The lengthy round-trip time for a radio signal — more than eight hours for Voyager 2 — imposes stringent reliability requirements on ground equipment. A combination of antenna size, radiated power, receiver sensitivity and signal processing, together with highly accurate frequency and timing, ultralow-noise receiving systems and monitor and control capabilities enables the DSN to overcome these challenges.

MISSION SUPPORT

Magellan

As the distance between Earth and the Magellan spacecraft at Venus decreased in 1991, the DSN switched its continuous daily support for Magellan from the 70-meter antenna subnetwork to the two 34-meter antenna subnetworks. The ability to capture Magellan's radar mapping data continued to improve. In January, the cumulative capture rate was 98.9 percent, well above the planned rate of 96 percent. By the end of the prime mapping mission in May, the DSN had captured 171,000 of a total of 172,500 minutes of data for a cumulative rate of 99.1 percent. Support with the 34-meter antennas continued with the first of six extended-mission mapping cycles — each to last eight months, or one Venusian year — beginning in May; during the first four months of this cycle the cumulative data capture rate improved to 99.2 percent.

The Magellan mission opened a new era in spacecraft navigation support: it was the first to use X-band (7.2 gigahertz) — a frequency less susceptible to interference by charged particles — in addition

to S-band (2115 megahertz) for uplink along with the standard 8.4-gigahertz X-band downlink. The resulting navigational accuracy provided the extremely precise pointing needed for Magellan's radar. The mission's requirements were met by using a "two-way minus three-way" X-band Doppler data technique, enabling Magellan to avoid the antenna time required by the DSN's Very Long Baseline Interferometry system for the necessary accuracy.

Galileo

The partial deployment of the Galileo high-gain antenna had many consequences. Numerous attempts to free the antenna necessitated extensive rescheduling to meet Galileo's tracking requirements during these demanding periods. A demonstration of the Galileo X-band uplink capability was deferred; tests of a new noise-overcoming decoder were postponed because the coded signal could not be transmitted using the spacecraft's low-gain antennas.

Galileo's encounter with the asteroid Gaspra was accomplished by using one of the spacecraft's two low-gain antennas with science data recorded for subsequent playback. The playback took days because the imaging data first had to be transferred from the onboard tape recorder to the spacecraft's command and data subsystem and then read out in engineering data as a subset of the 40-bits-per-second rate that the low-gain antenna could accommodate.

Hiten Aerobraking Support

The DSN supported the lunar swingbys of the Japanese satellite Hiten and provided 26-meter radio metric data and the vehicle's orbital parameters. Hiten, launched in 1990, successfully demonstrated aerobraking — a technique to reduce the quantity of fuel burned in making orbital changes — when it passed by Earth in its highly elliptical 12-day orbit. The Japanese Institute of Space and Astronautical Sciences determined that a perigee error of 5 kilometers would result in potentially damaging temperatures and heat fluxes on Hiten's surface. Perigee had to be predicted by DSN analysts to better than 1 kilometer for the final trim maneuvers.

Hiten completed two aerobraking technology demonstrations with perigees of 125 kilometers and 120 kilometers. Spacecraft orbital velocity at closest approach was 11 kilometers per second, within 0.1 kilometer per second of Earth escape velocity. The orbit solutions for maneuver design sent to the Japanese Institute were several factors of 10 better than required; DSN analysts had determined perigee to better than 20 meters.

The DSN plans to support aerobraking for Magellan later in its extended mission when attempts will be made to circularize the spacecraft's orbit around Venus.

Olympus Emergency Support

When the European communications and television broadcasting satellite Olympus lost attitude control in May, command was transferred from Fucino, Italy, to the European Space Operations Centre in Darmstadt, Germany, where a mission recovery team was assembled.

European Space Agency stations could not access Olympus while the satellite was rolling, and the DSN was asked to support the recovery attempt with its higher power transmitters, using the 26- and 34-meter stations at Madrid to transmit commands. Olympus was placed in a

safe mode, although it continued to roll. As the satellite moved out of position and drifted eastward, the 26-meter station at Goldstone transmitted commands to control the satellite's temperature in order to thaw its thruster fuel. Olympus was finally stabilized and achieved geosynchronous orbit. Goldstone continued to provide daily support for three weeks in July. JPL received a commendation from the European Space Agency's Board of Directors for the DSN's successful rescue effort.

ROSAT Emergency Support

The DSN assisted the German Space Operations Center by providing telemetry, command and radio metric data during recovery of the German–U.S. Roentgen (ROSAT) satellite, which had lost attitude control.

As a result of the near-catastrophic event, DSN support was scheduled to supplement that of the German Weilheim station. The DSN's 26-meter stations at Goldstone and Canberra have been tracking ROSAT on a two-pass-per-day basis to ensure the satellite's safety in case the attitude control problem recurs. NASA and the German space agency have agreed to continue this arrangement until the satellite's mission ends in January 1995.

ADVANCED SYSTEMS

Same-Beam Interferometry Demonstration

A new radio metric data tracking technique known as same-beam interferometry has been demonstrated and applied to improve orbit determination around Venus for Pioneer 12 and Magellan. The technique uses two or more stations to simultaneously receive signals from both spacecraft. Plane-of-sky components of the relative position and the velocity of each spacecraft are measured directly.

Thirty-five hours of same-beam interferometry data were acquired during three experiments at the Deep Space Communications Complexes in California, Australia and Spain in August 1990 and in February and April 1991. The angular precision of the measurements is better than 1 nanoradian or 600 millionths of a degree, which corresponds to a position error of about 100 meters at Venus. Orbit solutions for both spacecraft show a factor of three to five improvement in day-to-day consistency when same-beam interferometry and Doppler frequency shift data are combined. This technique will improve navigation for future planetary orbiters, rovers and landers.

New Frequency Standard

A first-generation, ultraprecise frequency standard was completed this year at JPL to meet challenging new requirements such as those imposed by radio science investigations planned for the Cassini mission. The trapped-ion frequency standard uses linear-electrode geometry to generate electromagnetic fields that confine mercury ions to a pencil-shaped region measuring about 2 by 50 millimeters. The technique prevents the ions from striking the walls of the container and reduces external disturbances so that the unperturbed internal structure of the ionized atoms can be used as a reference for the generation of precise signals.

The frequency of an auxiliary oscillator is compared with the characteristic frequency of the internal structure of the mercury ions when irradiated with ultraviolet light. When the two frequencies match, the ions absorb the ultraviolet light; otherwise, they remain transparent. The information is then used to control

and stabilize the frequency of the auxiliary oscillator, which provides the reference signal at its output. JPL data on the standard indicate a frequency stability of about one part in 10^{16} for measuring intervals longer than 10,000 seconds — equivalent to one second every three billion years. This is superior to all other known frequency standards. Verification of the ultimate stability awaits the development of a second unit.

Digital Receiver Application

An advanced digital receiver intended to provide greater sensitivity for deep space communications was demonstrated in 1991 for two spacecraft missions. The Advanced Receiver Exciter II (ARX II) will be placed in the Signal Processing Center at each Deep Space Communications Complex. The receiver accommodates higher and more variable data rates and is compatible with fast-moving Earth orbiters. Its improved signal-to-noise performance will enhance communications for deep space missions.

During the year, an ARX II prototype helped evaluate the experimental Ka-band transponder to be carried into space in 1992 on the Mars Observer spacecraft. The first operational version of the receiver was also demonstrated this year. It will be installed early in 1992 at the Signal Processing Center adjacent to the Goldstone 70-meter antenna to sustain communications with Pioneer 10, which is so distant that its signals will soon be too weak to be detected by the DSN's existing receivers.

Big Viterbi Decoder

Because of launch delays and trajectory redesign, the Galileo spacecraft will travel greater distances and have less available power than expected when its communications system was first designed in the 1970s. In anticipation of the benefits of a theoretical coding gain developed at JPL, a simple spacecraft encoder was installed on Galileo. The Big Viterbi Decoder has now been developed to validate the theory. The noise-overcoming decoder uses improved Viterbi architecture with a large number of JPL-designed very large scale integrated devices interconnected in parallel. The unit is programmable so that many codes can be used; it is the largest decoder ever built.

Construction and performance evaluation of the first Big Viterbi Decoder were completed in 1991. Tests demonstrated that the coding gain — measured as the reduction in required transmitter power for the same error rate in the received data — is approximately 1.5 dB, representing a 40-percent improvement. Spacecraft testing awaits the unfurling of Galileo's high-gain antenna.

Atmospheric Visibility Monitoring

Scenarios for the application of the deep space optical communications system of the future include both space-based and ground-based antennas that function as telescopes. The Atmospheric Visibility Monitoring stations being developed by JPL are designed to answer some of the questions associated with ground-based optical antenna systems.

The objective of the Atmospheric Visibility Monitoring project is to develop a statistical model of sky visibility over the southwestern United States by monitoring the brightness of 25 selected stars in the northern and southern hemispheres. Three observatories are being set up — at the JPL Table Mountain Observatory site in the San Gabriel Mountains, on Mt. Lemmon in Arizona and at a site to be determined in New Mexico or Texas. The first Atmospheric Visibility Monitoring observatory began operation at Table Mountain in November 1991.

TELECOMMUNICATIONS SCIENCE

SETI Sky Survey Prototype

A two-million-channel digital wide-band spectrum analyzer, designed and built at JPL for use in NASA's Search for Extraterrestrial Intelligence (SETI) project, passed system-integration tests in 1991 in preparation for a 1992 deployment at Goldstone. The analyzer features a no-waiting or "pipelined" architecture that performs 4.5 billion operations per second — faster than the speediest supercomputers. It can detect a weak interstellar signal in the midst of interfering radio signals that are a million times more powerful. Such sensitivity is required for SETI searches and for signal characterization tasks within the DSN. JPL is collaborating with the NASA Ames Research Center in the NASA SETI Microwave Observing project.

Orbital Debris Radar

During 1991, an improved chirp-radar system was developed to detect debris that is in elliptical rather than circular Earth orbits and to provide ranging information on the orbiting matter with 1-kilometer resolution. The system uses a personal computer with a commercial signal-processing board running JPL-developed algorithms.

For chirp operation, the 70-meter Goldstone antenna transmits signals and the 26-meter antenna 20 kilometers away receives the returns. The system detects a returned echo from a small particle passing through the intersection of the two antenna beams and performs most of the processing simultaneously with the observations. At the end of a track, data pertaining to the size, range and radial velocity of each particle are recorded on a floppy disk.

The system typically detected and recorded a 3-millimeter-sized particle with a radial velocity of 39 meters per second at an altitude of 561 kilometers. This capability is significant because even millimeter-sized particles could be hazardous to astronauts engaged in extravehicular activity on Space Station Freedom. The data can be used to improve orbiting-debris models so that safe orbits can be chosen for Freedom.

NETWORK UPGRADES

New Research and Development Antenna

In May, the DSN formally commissioned a new 34-meter antenna for communications research and development at frequencies as high as 32 gigahertz. Though this is well beyond the spacecraft frequencies used now, the Ka-band downlink for future deep space missions will be at 32 gigahertz to take advantage of its greater data capacity.

The new antenna uses a beam-waveguide system to channel microwave energy from the Cassegrain focus to low-noise amplifiers in the antenna pedestal — a distinct advantage over existing antennas in which the receiver and transmitter electronics are located on the reflector. The beam-waveguide design permits routine access for repair, replacement and upgrading without interrupting tracking operations.

The new antenna's main reflector is smooth enough to support research at frequencies approaching 40 gigahertz (7.5-millimeter wavelength), five times the frequency of X-band high-rate deep space communications. After its completion in June 1990, the antenna underwent testing and became operational with its formal commissioning. It is the first beam-waveguide antenna built by JPL and the precursor of a subnetwork of 34-meter antennas.

X-Band Acquisition Aid

Mars Observer will be the first spacecraft to be tracked exclusively in X-band (7-gigahertz uplink and 8.5-gigahertz downlink) by the DSN. The uncertainty in the spacecraft's position after its launch in 1992 may exceed the acquisition capability of the narrow beamwidth of the DSN's 34-meter deep space antennas.

An X-band acquisition-aid system was installed in October on the Canberra 26-meter antenna, which usually receives only S-band signals. The aiding system includes a 1.2-meter antenna and tracking feed with low-noise amplifiers mounted to the edge of the 26-meter dish. With a beamwidth of 4.4 degrees compared to only 5 minutes of arc for the 34-meter antenna that would normally be used and a maximum acquisition range of 80,000 kilometers, the system is sensitive enough to acquire the spacecraft signal beyond the initial position uncertainty. The acquisition-aid system was designed by Bendix Field Engineering Corporation and fabricated by Scientific Atlanta Corporation, both JPL contractors.

Deep Space X-Band Transponder

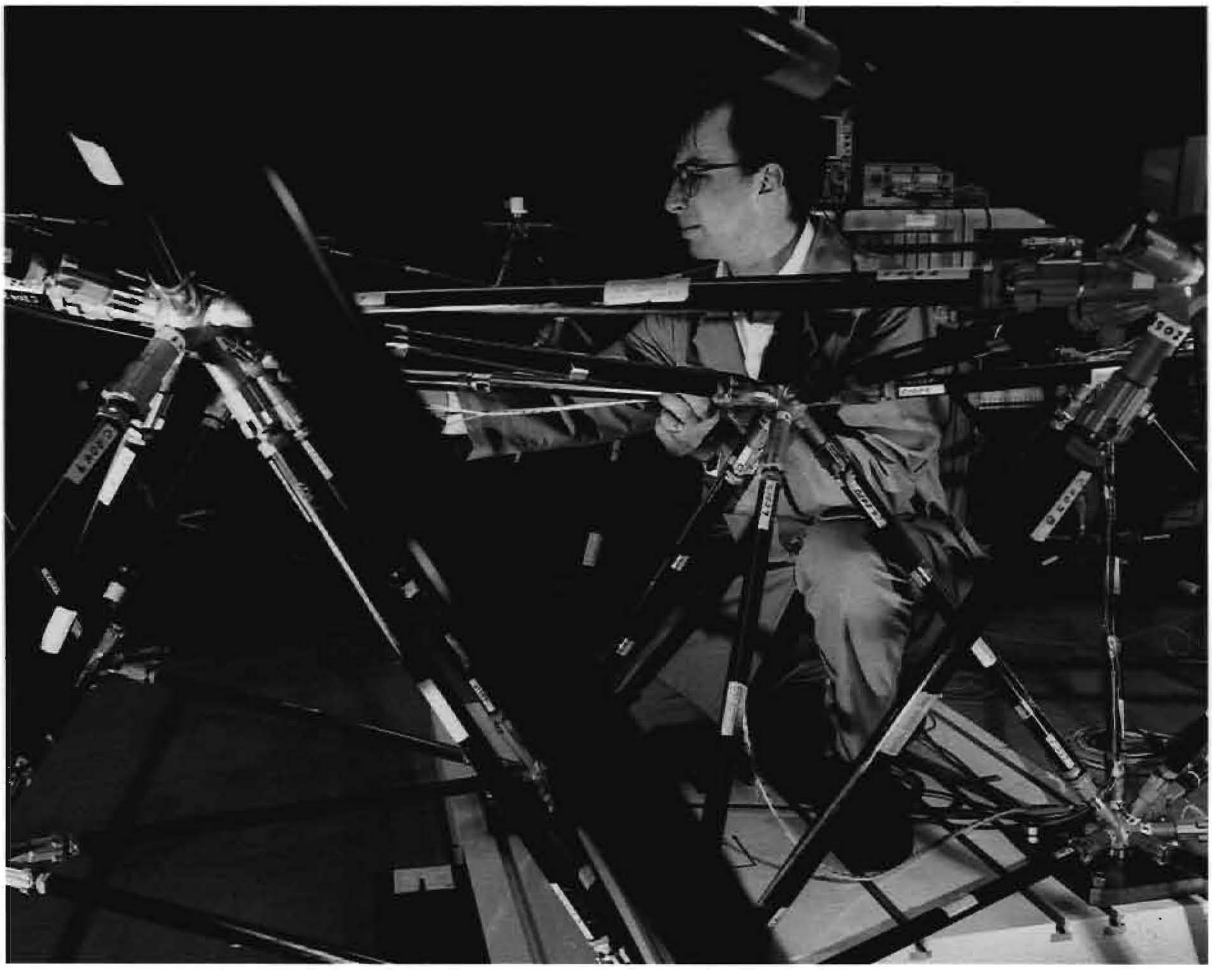
In the 1980s and for the early 1990s, the Magellan, Galileo and Mars Observer projects needed X-band transponders that would meet stringent radio navigation requirements. Now, a more compact, efficient and sensitive X-band transponder is being readied for new projects.

An engineering model completed final testing in October. The transponder includes JPL-originated innovations in component technology and architecture for greater radio navigation stability. Motorola developed the unit for JPL and devised improved fabrication techniques to realize the refinements. The design demonstrates considerable mass, volume and power savings and better receiver noise performance than current transponders.

THE 70-METER ANTENNA AT GOLDSTONE. INSET: JPL'S MAIN MACHINE SHOP FABRICATES ALL OF THE DSN'S U.S.-MADE ANTENNA FEED CONES. EACH ALUMINUM ALLOY SECTION, MADE TO TOLERANCES OF ± 0.002 INCH, TAKES OVER 100 HOURS TO COMPLETE.

JPL lays the *groundwork for future space missions* by exploring concepts and developing prototypes in a variety of critical areas. Ongoing refinements in automation — knowledge systems, telerobotics and rovers — continue to reduce mission costs and enhance science returns. Propulsion technology research *leads to efficient, reliable systems* for the distances required for space travel and exploration. New propulsion techniques also improve the performance of Earth-orbiting satellites. Advances in microsensors, microelectronics *and optical systems contribute to* studies in astrophysics, Earth remote sensing and communications. During 1991, the Laboratory's work in microsensors and microinstruments included *a new type of infrared sensor* and demonstration of a sensitive, small-mass seismometer. On a larger scale, research continued in a materials and structures program for the development of space-deployable, multisegmented reflectors. Such instruments require sensitive optics *combined with lightweight structures* that can be assembled precisely in space or on the Moon. JPL also made progress in electronic neural networks *and advanced computing* systems for modeling and complex problem-solving activities.

THE NEW CRAY Y-MP2E/116 SUPERCOMPUTER SOLVES COMPUTATIONALLY INTENSIVE PROBLEMS. THE CRAY IS PART OF A CALTECH AND JPL EFFORT TO OFFER SUPERCOMPUTING CAPABILITIES AT JPL AND REMOTE SITES VIA NASA NETWORKS.



A TEST BED FOR A MULTISEGMENTED-MIRROR TELESCOPE. THE BACKUP STRUCTURE FOR THE MIRROR SEGMENTS, IT WILL UNDERGO TESTS SUCH AS FIGURE CONTROL IN WHICH SEGMENTS ARE ALIGNED TO FORM A PRECISE PARABOLIC SHAPE.

SPACE AUTOMATION AND ROBOTICS

The Space Automation and Robotics Program develops roving vehicles, knowledge systems and telerobots. In addition to cost-saving benefits in building and operating space systems, automation enhances performance and provides Laboratory controllers with vital tools for handling concurrent mission operations.

Knowledge Systems

In addition to knowledge systems that are used to support JPL's flight projects, other systems are being more broadly applied across NASA and the aerospace community. Working with other NASA centers and McDonnell Douglas Space Systems, JPL used an artificial intelligence system to generate complex schedules for the power system of the Space Station Freedom and for the Shuttle Experiment Simulator, which develops preflight astronaut procedures. The Operations Mission Planner follows the routines of a typical human scheduler by searching for good, rather than mathematically perfect, schedules. It relies on heuristics and minimally disruptive replanning to identify and resolve conflicts and compress plan-generation time.

Selective Monitoring (SELMON), a system for coping with the ever-increasing numbers of sensors and data channels in space systems, was evaluated on the test bed for the Space Station's environmental control and life-support subsystem. SELMON assesses the effectiveness of sensor placement during system design and automatically identifies the most relevant and informative sensors in each operating mode.

Another prototype knowledge system was demonstrated with Galileo magnetometer data. Developed in conjunction with plasma physicists from the University of California, Los Angeles, the Pipeline Instrument Via Plan Inspection package helps link specialized data analysis and management functions into large, integrated processes for analyzing and displaying science data. The Pipeline package detects inconsistencies and suggests optimized methods of organization, which reduces time spent in preparing and analyzing large data sets and lowers costs by minimizing time wasted on erroneous processes.

Telerobotics

Teleoperator and supervised robotic systems are being developed at JPL for on-orbit assembly and maintenance, science sample handling and terrestrial operations. Both types use instrumented mechanical arms to perform tasks, but teleoperator systems rely on humans using hand controllers to interpret sensory data and issue motion commands while supervised robots perform tasks automatically under human monitoring. A third type, telerobot systems, combines teleoperator and supervised-robot elements.

The Supervised Telerobotics Laboratory demonstrated the feasibility of ground-controlled space telerobot operations by completing typical servicing tasks such as exchanging instrument modules, installing an electrical connector and removing an electronics panel from a mock-up. JPL telerobots successfully duplicated repair activities performed by two astronauts on the Solar Max Satellite in 1984. The Advanced Teleoperations Laboratory demonstrated a control mode that senses forces generated by the robot's contact with its environment — for example, encountering a wall — and feeds back signals to the operator's hand controllers. This provides a tactile perception of the robot's behavior for the operator and enhances the ability of telerobots to perform delicate operations.

A computer graphics interface has also been developed in which the telerobot operator's hand controllers drive a high-fidelity, real-time graphical simulation of the robot and the task area. The interface simulates the tactile effects of robot–environment contact and feeds the

information back to the hand controllers. The visual–tactile simulation allows the operator to preview the effects of commands, improving performance and reducing the risk of damage. Similar techniques are being used in developing controls for high-dexterity robot arms.

Space Automation Research

JPL demonstrated a trainable identifier network for estimating the values of engineering parameters associated with unknown loads to within 1-percent accuracy. Developed with Caltech, the identifier is based on neural networks and is part of an investigation into the use of learning neural networks, global optimization and adaptive techniques for controlling interactions between robots and loads with poorly known dynamic characteristics. Based on biological models, such networks are trained off line to respond to the anticipated characteristics of an assumed dynamic model of the load. In operation, the networks observe the behavior of a robot interacting with the load and calculate parameters to reconcile the load model with the observations.

JPL engineers constructed an experimental apparatus using a robot arm and a programmable load with variable dynamic characteristics and then implemented a learning algorithm and network circuit as analog chips. Application of these ideas could increase the stability and performance of systems operating for long periods without human intervention and maintenance.

CENTER FOR SPACE MICROELECTRONICS TECHNOLOGY

JPL's Center for Space Microelectronics Technology supports NASA and Department of Defense space mission work by developing and evaluating electronic and optical concepts for improved sensors, real-time signal processing and high data rate information processing and storage. Researchers explore ideas for solid-state devices for potential space applications and develop the technological base for advanced space computing concepts and architectures. The Center annually hosts several distinguished visiting scientists and conducts workshops on special research topics.

Advanced Sensors

JPL researchers demonstrated a prototype microseismometer with a mass of less than 150 grams. Its position-sensing method, developed at JPL's Microdevices Laboratory, uses a capacitance-detection system with subangstrom sensitivity. The detection system and a silicon micromachined mechanical structure together produce an acceleration sensitivity of one billionth of a gram, equivalent to conventional seismometers of 10 to 100 times greater mass.

The concept of electron tunneling was applied to an infrared detector and demonstrated by JPL in 1991. Infrared radiation is absorbed by a micromachined structure, causing the expansion of a volume of trapped gas that deflects a thin membrane. An electron tunneling displacement transducer senses the expansion by monitoring changes in tunneling current between a gold-coated silicon tip and a gold film on the membrane. Because the transducer is sensitive to changes in separation as small as a thousandth of an angstrom, very small amounts of radiation can be detected. The sensitivity of the prototype tunneling infrared detector is already competitive with that of the best broadband uncooled infrared sensors.

A milestone in preparation for explorations at submillimeter wavelengths was achieved with a quasi-optical receiver operating at 500 gigahertz that meets the sensitivity requirements for NASA space missions. Using electron-beam lithography, Caltech and JPL researchers

designed and fabricated mixers for the receiver based on superconducting niobium–aluminum oxide–niobium tunnel junctions. The Caltech Submillimeter Observatory in Hawaii will use the receiver.

The Microdevices Laboratory made significant advances this year in developing Josephson devices that employ high-temperature superconducting thin films. Scientists demonstrated devices using coupled superconducting and nonsuperconducting layers of the compound yttrium–barium–copper oxide with a transition temperature of 90 kelvin. With their improved electrical characteristics, the devices may be useful for sensitive magnetic-field detectors, high-frequency sources and detectors and high-speed, low-power digital logic applications.

Long-Wavelength Infrared Focal Plane Arrays

A silicon-based infrared device — an internal photoemission detector using a silicon–germanium heterojunction — was demonstrated this year. It detects visible to very long infrared wavelengths (more than 27 micrometers) and was fabricated by depositing thin silicon–germanium alloy layers on silicon substrates by molecular-beam epitaxy. As many as 16,000 detector elements have been integrated with silicon readout devices to form large, inexpensive focal plane imaging arrays.

Photonics

The Laboratory's photonics program designs and fabricates semiconductor diode lasers for applications in spectroscopy, communications and computing. During the year, prototype near-infrared lasers were developed and delivered to NASA Langley Research Center and Goddard Space Flight Center for system tests. The prototype devices will be used for injection locking — a method whereby one laser stabilizes the frequency of a second laser's oscillator — of titanium–sapphire solid-state lasers in an atmospheric-sensing experiment. A semiconductor laser structure for emission of mid-infrared radiation was demonstrated that could have spectroscopic applications or use as an injection-locking source for solid-state lasers.

Arrays of detector–amplifier–emitter "neuron" pixels were fabricated in a Caltech–JPL quest for optoelectronic neural networks with ultradense interconnecting optical "synapses." The pixel arrays can be used in applications such as image processing. Researchers achieved record contrast ratios larger than 60 to 1 in a low-power, optically addressed spatial light modulator based on multiple quantum-well structures fabricated by molecular-beam epitaxy.

Electronic Neural Networks

A human brain accomplishes recognition, association, deduction and optimization through its massively parallel architecture, with billions of neuron cells communicating asynchronously among themselves through trillions of synaptic interconnections. In electronic neural networks, many simple processors mimic the neurons and simultaneously communicate among themselves through networks of variable-strength connections or synapses.

Neural network architectures have evolved at JPL that capture the functions of supervised and unsupervised learning, pattern recognition and image interpretation. They have potential space, industrial and defense applications, including guidance and control, robotic control, planetary rover path planning, image and speech processing and multispectral data classification. Electronic neural network technology developed by JPL for space and defense applications is now being transferred to U.S. industry.

This year, the Laboratory implemented an asynchronous neural network for the solution of such complex dynamic problems as weapon-to-target assignments and resource-to-consumer allocations. In these computation-intensive problems, the possible assignment combinations mount factorially; for example, when pairing 64 resources with 64 consumers, the total pairing combinations exceed 10^{89}. The neural network produces a solution in a fraction of a millisecond, achieving a speed more than 10,000 times that of advanced parallel processing machines (such as hypercubes) operating with conventional algorithms.

In another important advance, JPL developed a fine-grain, massively parallel processor for determining a vehicle path consuming the least energy over a given terrain. The hybrid digital–analog processor, which was designed to solve military terrain trafficability and tactical mobility analysis problems, promises to increase the available computing speed by several orders of magnitude over conventional techniques.

ADVANCED OPTICAL SYSTEMS TECHNOLOGY

The Laboratory's research in optical systems technology will provide new solutions to the problems of designing precision optical systems for space astrophysics, extrasolar planet detection, Earth remote sensing, planetary exploration and communications. NASA and the Department of Defense sponsor these technology efforts; some activities include collaboration with institutions funded by the Department of Energy, such as Lawrence Livermore National Laboratory.

Precision Segmented Reflectors

JPL and the NASA Langley Research Center completed a five-year phase of a program addressing technologies for a multisegmented-mirror telescope to be deployed in space or on the Moon. Advances were made in composite materials for mirror substrates and replication techniques for fabricating optically smooth mirror surfaces on the new materials. The program has also developed the capability for space-erectable structures and controls necessary to mount and position the mirror segments in the shape of a single parabolic reflector. These successes move NASA closer to building and flying an observatory for astronomical studies at submillimeter wavelengths.

A major challenge is to produce a precise segmented surface for accurate operation at wavelengths as short as 50 micrometers. Lightweight, thermally stable reflector segments of graphite–epoxy composites must operate between room temperature and the substantially lower temperatures of deep space. Half-meter reflector segments were fabricated with combined figure accuracy and thermal stability of less than 3 micrometers between 300 and 200 kelvin. This was achieved without significant focus shift, which is a critical requirement. One-meter reflector segments based on more advanced designs and materials are now being evaluated with expectations of even better performance at temperatures as low as 100 kelvin.

To meet the precision control requirements, JPL designed a two-step figure-control system. Individual segments are aligned to form a single parabolic surface and a set of positions is found that creates the sharpest image of a reference star. The segments are then controlled by an onboard position-measurement system in which laser beams detect all possible motions of the segments and generate compensating actuator corrections.

Control Structure Interaction

JPL technicians have sought to reduce vibration-induced image distortion in lightweight space-based optical systems by a factor of 10,000. They demonstrated a 4,000-fold reduction in 1991; further reductions will be achieved by increasing the isolation between optical components and onboard motors, actuators and spacecraft controls. Most challenging are space-based interferometers that must maintain the distance between widely separated optical elements to within a few billionths of a meter. A test facility was completed this year that resembles a partial space interferometer, including a laser star simulator, a metering truss structure, an optical pathlength delay line and associated instrumentation and real-time control computers.

The effectiveness of vibration-damping systems is dependent on the precise placement of passive and active damping devices in the total structure. This year, JPL combined mathematical techniques for the optimal location of damping elements with other design tools for the integration of vibration control in the structural design process. Initial experimental results with just one optimally placed device produced a 25-fold reduction in vibration.

Precision Optical Delay Lines

JPL will provide the precision optical delay lines and beam-combining apparatus for the second 10-meter telescope at the Keck Observatory on Mauna Kea, Hawaii. NASA became a partner in the observatory last year. The JPL contribution will allow the two 10-meter telescopes to operate as an 80-meter-baseline optical interferometer. Since the Keck interferometer may eventually include four additional telescopes, the delay lines and beam combiner will be designed to accommodate six telescope beams.

Optical interferometers — consisting of two or more telescopes arranged so that their beams can be combined to form centrally located interference patterns — measure the precise positions of stars and can obtain very high resolution images of astronomical sources. The precision delay lines equalize the optical paths from the star through each telescope and into the beam combiner. The pathlengths must be equal to a small fraction of the light's wavelength, and the delay lines must equalize the pathlengths to within a billionth of a meter while compensating for pathlength changes caused by Earth's rotation with respect to the star.

Adaptive Optics

Turbulence in Earth's atmosphere blurs the images acquired by ground-based telescopes and degrades a telescope's imaging ability from theoretical performance levels. An adaptive optics system corrects for this by measuring the atmospheric distortion and forming a compensating distortion in a deformable mirror. The Laboratory began an adaptive optics research program in 1991 to detect and correct optical distortion in the Keck Observatory's 10-meter telescope. NASA's decision to become a partner in the Keck Observatory and its related mission objective — to detect planets and protoplanetary material in orbit around other stars — created a need for adaptive optics suitable for the 10-meter telescope.

Integrated Modeling of Optical Systems

A computer program for predicting the performance of complex optical and sensor systems, rather than simply their components, was demonstrated by the Laboratory this year. The program models the geometrical and wave-propagation performance of optical systems subject to thermal distortions and mechanical disturbances and can take into account new or uncommon elements such as segmented and deformable

mirrors. In the future, the program will be able to predict the effects of imperfect detectors and signal-processing electronics on sensor output.

ADVANCED PROPULSION TECHNOLOGY

In the 21st century, increasingly large and sophisticated spacecraft will travel to destinations throughout and beyond the solar system. In addition to new solar- and nuclear-powered ion propulsion systems, which promise high performance, numerous advanced propulsion ideas are being researched in the "proof-of-concept" stage.

Ion Engine Technology

JPL is working to verify the reliability of ion engines for lengthy planetary missions. The performance of these low-thrust engines is well established through experiments and flight tests, some dating back nearly 30 years, but their ability to operate satisfactorily for extended periods in space is less certain. During 1991, a cathode suitable for a 5-kilowatt xenon–ion engine was operated successfully for 5,000 hours, an important step in demonstrating the feasibility of long-life ion propulsion systems.

The high cost of life-testing has been a principal barrier in engine qualification, but a design change originated at JPL could significantly lower the costs of full-duration life tests of high-powered xenon–ion engines. Life tests of these engines have been prohibitively expensive because of the need for large vacuum systems and elevated pumping speeds in excess of 350,000 liters per second. Without these high pumping speeds, charge-exchange ions produced as a result of the imperfect simulation of a space environment erode the engine at rates higher than anticipated in space. JPL researchers resolved this problem by adding a negatively biased third grid to the ion accelerator system to collect the positive charge-exchange ions before they erode the engine. Tests and calculations indicate that the technique can reduce the required pumping speed by an order of magnitude. With lower pumping speeds, ion engines can be life-tested in modest vacuum facilities within the resources of existing technology programs.

Fullerene Electrostatic Propulsion

JPL began research this year on the carbon-60 ion engine. The recently discovered giant carbon molecules — particularly carbon-60 — appear to be ideal propellants for electrostatic propulsion systems. Called "fullerenes," the molecules have a combination of useful qualities: large molecular mass, a low first-ionization potential, extreme resistance to fragmentation under electron bombardment and minimal effect on the engine's life-critical metallic surfaces.

An ion engine using carbon-60 as a propellant could be more than twice as efficient as advanced ion engines at specific impulses in the 1,000- to 1,500-second range. A carbon-60 engine would work well for applications such as geostationary satellite stationkeeping and Earth-orbit transfer missions. Fullerene ion propulsion systems generating significantly higher specific impulses than today's electric propulsion systems may also play a key role in piloted space exploration missions.

SPACECRAFT POWER TECHNOLOGY

Advanced Photovoltaic Solar Array

A prototype of a flexible, foldout system that promises to quadruple the power-to-mass ratios of existing spacecraft arrays maintained complete structural integrity during ground vibration and acoustic

launch simulations of the space shuttle and Atlas rocket. The system contains minimal-mass electrical and structural components that reduce overall mass to only a quarter of conventional arrays with equivalent power.

Three additional solar panels were added as an upgrade to the original six-panel array, enlarging overall dimensions to 2.8 by 4.5 meters. The extra panels contain 100-micrometer gallium arsenide–germanium solar cells that augment the panels' silicon solar cells. The added ultrathin cells boost power density by 30 percent over that of the original silicon solar cells. Successful assembly of such fragile devices in a manufacturing environment was an important milestone.

High-Energy Rechargeable Lithium Battery

JPL researchers are at work on rechargeable lithium cells that have high specific energy and high energy density and can operate at ambient temperature. Efforts have already resulted in AA cells (the familiar household size) with specific energy of 125 watt-hours per kilogram and specific density of 250 watt-hours per liter, which is triple the comparable figures of merit for nickel–cadmium cells. Increased energy storage capacity and smaller, lighter lithium batteries that use less payload volume than nickel–cadmium cells would be of great benefit in space travel.

High-Power Bipolar Lead–Acid Battery

The development of a lead–acid battery for space applications requiring high pulse power was completed by the Laboratory in 1991. Several prototypes are capable of generating high power pulses lasting 15 to 20 seconds for tens of cycles at specific power levels in excess of 1 kilowatt. This capability is three to four times greater than that expected from advanced automobile batteries. The 5-kilowatt and 25-kilowatt prototypes were built under contract to JPL by Johnson Controls, Inc.

The battery consists of a stack of bipolar electrodes sandwiched between two end electrode assemblies. Each electrode, made of a thin current-collector plate separating the positive (lead dioxide) and negative (lead) plates of adjacent cells, adds 2 volts to the overall battery potential. Lighter weight and corrosion-resistant hardware could increase the peak specific power to 2.5 kilowatts per kilogram with as many as 1,000 cycles. Batteries such as these could be used in planetary rovers or electric cars.

One of the strengths of this technology is the existence of a well-developed industrial infrastructure for lead–acid batteries that consists of manufacturing facilities, scientific expertise and recycling capability. The lead–acid couple has high open-circuit voltage, low electrolyte resistivity, very low cell resistance and high efficiency, making it ideal for high-power commercial and defense applications.

OTHER TECHNOLOGICAL ADVANCES

Sorption Cooler Technology

JPL successfully demonstrated the technology for a cryogenic sorption system capable of cooling the infrared detectors of instruments on observation satellites down to 10 kelvin, so that they can operate at peak sensitivities. Sorption refrigerators use a heat-powered chemical alternative to the mechanical compressors of typical refrigeration systems. The technology is unique in its potential to meet the increasingly demanding needs of future space missions for devices that can cool loads from 65 kelvin down to 10 kelvin in less than 2 minutes and are capable of reliable, vibration-free operation for 10 years.

The device uses a quick-cooldown hydride sorption refrigerator that freezes liquid hydrogen and then cools it to 10 kelvin. The hydrogen is collected in hydride sorbent beds where it can be repressurized and used again. The fully recyclable system generates negligible vibration. Cooldown from 80 to 10 kelvin was achieved in under 2 minutes and the cooler operated below that for 45 minutes while absorbing a simulated sensor heat load of 150 milliwatts. The reservoir was also tested upside-down to demonstrate that the capillary forces in a wick designed to retain liquid hydrogen could overcome gravitational forces — evidence that the system can operate in a zero-gravity space environment.

To verify the cooler's ability to achieve a 10-year life, a spaceflight demonstration experiment on the Shuttle Pallet Satellite mission is planned for 1994. Cryogenic cooler technology may be applicable to many NASA programs in Earth science, astrophysics and interplanetary science.

Force-Limited Vibration Testing

The Laboratory has developed a method of conducting spacecraft equipment vibration tests that more closely simulates a real-life vibration environment at launch. Testing is tailored to identify design and workmanship problems without inducing artificial failures that would not occur at launch. Less destructive types of vibration tests are essential to JPL's protoflight test approach in which testing is often conducted with one-of-a-kind flight hardware to save time and expense.

In conventional vibration tests, the input vibratory motion is specified but the reaction force from the test item to the vibration machine is ignored. Most test failures occur when the test item goes into resonance and the reaction force becomes very large. The large reaction force is recognized as an artifact that does not occur with the lightweight, flexible mounting structures characteristic of spacecraft and space vehicles. In force-limited vibration tests, the motion and force provided to the test item are controlled so that the vibration experienced by the test item is as it would be in flight. Reaction force limiting was used successfully at JPL in three vibration tests of flight instruments during the past year. The technique is likely to be widely employed soon within NASA and eventually in all industries where equipment must be qualified to severe vibration environments.

Digital Autocorrelators for Space Spectrometers

Advances in very large scale integration technology have created opportunities to implement signal-processing algorithms — such as an autocorrelation function for a spaceborne spectrometer — in application-specific integrated circuits. This technology will initially reduce the power requirements for digital autocorrelation by a factor of at least 5 or 10 and ultimately by much more.

In one planned experiment, an autocorrelator spectrometer using JPL-designed correlator chips fabricated by Raytheon will make balloon-borne observations of interstellar oxygen. The 26-channel autocorrelator chip array requires 150 milliwatts DC per channel compared to 500 to 1,000 milliwatts for comparable devices using individual integrated circuits. The balloon flights are a joint effort of the Laboratory and the University of California, Santa Barbara. In addition, JPL and the University of Idaho have designed and are now testing another low-power correlator chip requiring 10 milliwatts per channel for narrowband spectrometer applications.

Features of digital autocorrelator spectrometers that make them useful spaceborne instruments include long-term stability, small size, low DC power

requirements and an ability to reduce data rates for downlink transmission. Digital autocorrelators have applications in millimeter and submillimeter spectrometers and spectral-line radiometers in astrophysics missions; they can also be used in balloon and spaceborne instruments to measure atmospheric chemicals for studies of ozone depletion and greenhouse effects.

Spacecraft Control System

Computational performance is a vital issue in the design and verification of control systems for spacecraft that have major components mounted on flexible booms. It is especially critical for hardware-in-the-loop testing when spacecraft simulation must be done in real time: the rate for a simple 20-degrees-of-freedom simulation model of the Galileo spacecraft running on a supercomputer is 10 times slower than real time. In addition, advanced algorithms and existing serial computers are too expensive for this purpose.

To address the problem, JPL developed a highly efficient algorithm for use on current low-cost parallel computers. The Dynamics Algorithm for Real-Time Simulation is based on spatial operator algebra, which is the application of several branches of applied mathematics to the analysis of the dynamic behavior of complex mechanical systems. The algorithm has demonstrated a speed at least 10 times greater than that of other algorithms and has been adopted for the development of a real-time hardware-in-the-loop simulator for spacecraft testing.

Innovative Software Development Tools for Flight Multicomputers

JPL is developing a fault-tolerant multicomputer system suitable for general-purpose applications on NASA spacecraft. A software tool set was completed that encourages innovative approaches to the problems of programming fault-tolerant parallel computers. The system incorporates high-level flowchart descriptions of flight software into the flight code. The computer's operating system uses this information to dynamically allocate resources such as processors and memory and to automatically reconfigure hardware and software when faults occur.

To exercise the software tool set, specialists developed a prototype command executive program for autonomous planetary rovers. The program is required to receive mission commands, ensure their consistency with the current rover environment and monitor their safe execution. The tools were used to develop a modular, high-level organization for the program, develop and verify the software implementing each module and test and analyze the performance of the resulting system.

Simulating Cosmic-Ray Effects

JPL has developed a new method of simulating the effects of single-event upsets — the potentially damaging interactions between cosmic rays and spaceborne microelectronics. The usual method for simulating cosmic-ray effects involves an expensive, time-consuming process in which devices are exposed to high-energy, heavy-ion beams using large particle accelerators. These tests expose an entire integrated circuit, so the most sensitive regions of the circuit cannot be identified.

JPL's technique uses a laser beam that scans in a controlled manner to identify areas on the integrated circuit that are sensitive to single-event upsets; the beam is then focused on selected locations to test individual circuit elements. The Microelectronic Advanced Laser Scanner can vary laser energy, wavelength, pulse duration and other parameters in determining the threshold value, depth and location of the circuit's most sensitive regions. Initial results show close agreement

between parts characterized as "soft" to cosmic rays after ion-beam exposure and those sensitive to laser upsets. The new laser scanner technology is an efficient, cost-effective way to screen integrated-circuit parts and identify sensitive elements in circuits.

Fiber-Optic Tactical Local Area Network

In a program for the U.S. Army, JPL designed an interface (message buffer) that enables users of fiber-optic local area networks to transmit real-time voice and video traffic in a packet format while simultaneously sending computer data. Normally, the bursts of energy associated with the packet format are unacceptable for voice or video transmission.

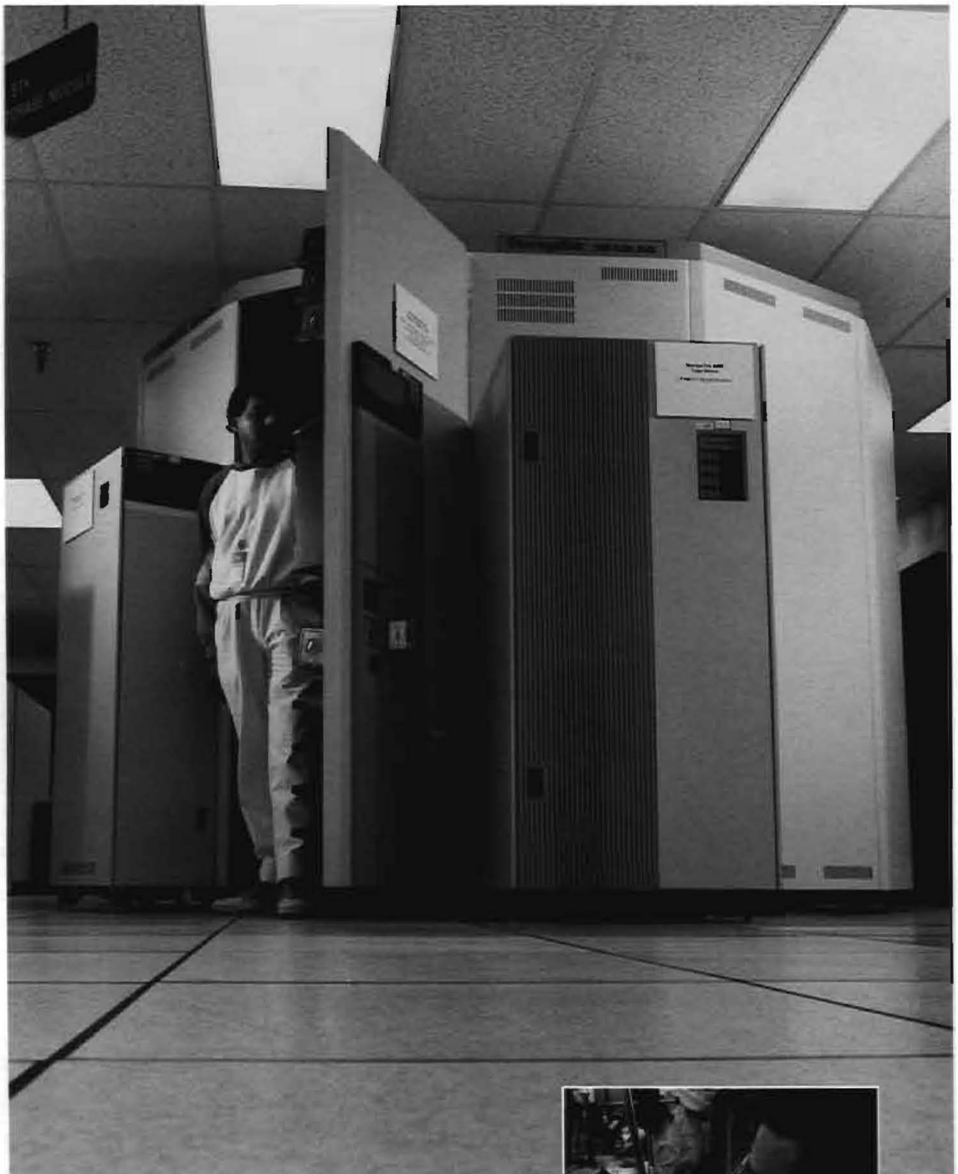
A test bed combining the interface with off-the-shelf hardware to upgrade existing networks is being prepared to demonstrate the feasibility of satisfying command, control and communication needs using a battlefield-deployable fiber-optic local area network. Hardware design, modeling, layout and systems design were completed during the year. Final board fabrication, testing and system integration are scheduled for 1992, to be followed by field tests in 1993.

These techniques may also be applied in NASA's space and terrestrial projects. Fiber-optic networks could interconnect high data rate instruments, such as synthetic aperture radars and multispectral imagers, with a laser communication downlink. For ground-based applications, the rapid deployment capability of fiber-optic tactical local area networks might help simplify cable layout for data–voice–video networks in mobile tracking stations.

Biocatalysis for Energy Conversion

In 1991, JPL completed 12 years of managing the national Biocatalysis Project for the Department of Energy's Office of Conservation and Renewable Energy. Project management now reverts to Department of Energy Headquarters, though Caltech and JPL will continue work in biocatalysis.

The project focused on the transfer of chemical and biochemical technologies to industry. Notable among its accomplishments were increases in bioreactor throughputs by two to three orders of magnitude, initiation of a program of biocatalysis by design, formation of three biotechnology companies and provision of major funding for the Materials Simulation Center/Biotechnology Institute at Caltech's Beckman Institute.



THE INTENSIVE RESEARCH AND DEVELOPMENT EFFORTS AT JPL REQUIRE SYNERGISTIC TEAMWORK, COMPREHENSIVE DOCUMENTATION AND MASSIVE DATA ARCHIVING. THIS AUTOMATED ARCHIVAL SYSTEM STORES UP TO 1.2 TRILLION BYTES OF DATA.

The Laboratory's *technical applications projects* make vital contributions to the national interest and assist industry in developing advanced engineering and science technology for commercial use. Much of the expertise initially *developed for space purposes* is channeled into work for sponsors such as the Department of Defense, the Department of Energy and the Federal Aviation Administration. JPL products *played a prominent role in* the Middle East during Desert Shield and Desert Storm operations. Because of the Laboratory's skills in rapidly fielding software-intensive systems, JPL was assigned a spacecraft development project that is part of *the Strategic Defense Initiative*. Several applications projects neared completion in 1991, including the All Source Analysis System, a networked, field-deployable, computer-based system for analyzing battlefield intelligence. *Work progressed on* two projects for the Federal Aviation Administration that are designed to increase the efficiency of *the nation's air traffic system*: a processor that combines and displays data on clear-air turbulence and other weather information and an advanced voice switching and control system *for aircraft controllers*.

A SOLDIER DEPLOYS THE ALL SOURCE ANALYSIS SYSTEM COMMUNICATIONS MODULE, WHICH MAINTAINS A LINK BETWEEN BATTLEFIELD INTELLIGENCE-GATHERING SENSORS AND THE SYSTEM'S CENTRAL COMPUTERS.

THE ALL SOURCE ANALYSIS SYSTEM, CAMOUFLAGED TO BLEND INTO SURROUNDING SCENERY, IS DESIGNED TO OPERATE NEAR A COMBAT ZONE TO COLLECT, ANALYZE AND RELAY INFORMATION ON ENEMY TROOP MOVEMENTS AND DISPOSITION.

MINIATURE SEEKER TECHNOLOGY PROJECT

JPL is developing a small Earth-orbiting satellite for the Air Force Phillips Laboratory as part of the Miniature Seeker Technology Integration project within the Strategic Defense Initiative (SDI). The Laboratory will develop and test a spaceborne sensor package to observe flight demonstrations of a ground-launched missile interceptor. The program takes advantage of ongoing seeker-component developments of other Strategic Defense Initiative Organization efforts. JPL will design and demonstrate an integrated sensor package containing a number of sensors developed for SDI programs to collect plume data and high-resolution imagery in flight for postflight analysis of interceptor demonstration missions.

SOFTWARE-INTENSIVE SYSTEMS

JPL applies an innovative, evolutionary approach to the development of software-intensive systems. Known as the rapid deployment method, the Laboratory's approach is an outgrowth of prototyping techniques but is procedurally more rigorous. The technique has been applied successfully to over 25 deliveries for a variety of users and systems.

Rapid deployment is distinguished from conventional single-delivery methodology by four tenets: extensive user involvement, incremental delivery, requirements feedback at each delivery and progressive formality. Users participate in all phases of system development from requirements evaluation through acceptance to operation. The feedback from each delivery promotes an evolving understanding of the system to help modify requirements for subsequent deliveries. The concept of progressive formality recognizes that processes and products evolve in the course of deliveries.

Rapid deployment overcomes the uncertainties and shuffling of requirements associated with conventional system development. Frequent deliveries maintain customer involvement, develop confidence, stimulate thinking about customer operations and offer immediate evidence of satisfactory performance by the project team.

COMMAND CENTER PROJECT

A project for the U.S. European Command (USEUCOM) integrates information from approximately 100 communications and automation systems to serve the staff in executing command and control. The system is being developed using the rapid deployment method.

During the year, JPL made its second incremental delivery of hardware and software to the USEUCOM battle staff. This included a local area network spanning eight buildings with automation capability for handling messages and maps, preparing briefings and preparing, coordinating and releasing situation reports. JPL supplied magnetic-media interfaces to the World Wide Military Command and Control System and the European Theater Army Command and Control System. The first products delivered were used in support of Desert Storm; the second delivery was used in USEUCOM's assignment as the lead agency in coordinating and directing the U.S. Kurdish relief efforts.

COMMAND AND CONTROL AUTOMATION PROJECT

JPL completed development, installation and test of an interim Command Center system for the U.S. Transportation Command (USTRANSCOM) at Scott Air Force Base in Illinois. The Command is responsible for providing global air, land and sea transportation to meet U.S. national security objectives. This encompasses worldwide strategic mobility planning, centralized transportation management and operations and integration of automated data processing systems for transportation.

The JPL-developed system consists of a number of workstations, large-screen displays, graphic equipment and database management resources. It provides senior-level officers with an automated command and control capability for making informed decisions in the management of USTRANSCOM's transportation assets. The system was successfully employed for both Desert Shield and Desert Storm operations.

VOICE SWITCHING AND CONTROL SYSTEM

JPL is providing technical assistance to the Federal Aviation Administration (FAA) for the development of an advanced voice switching and control system. The system's telephone links allow air traffic controllers to communicate with one another and with pilots in flight in an effort to increase the efficiency and reliability of the national air traffic control system. In 1991, the Laboratory built and demonstrated a model of an interim communications system for use in the event of slippage in the production schedule. A traffic simulation unit delivered a year ago was used to test prototypes of the new voice switching and control system. At the end of the year, the FAA selected a contractor to proceed with production.

REAL-TIME WEATHER PROCESSOR PROJECT

In 1987, JPL began developing the Real-Time Weather Processor for the FAA as part of the National Airspace System Plan to upgrade the U.S. air traffic system. In 1991, the Laboratory introduced enhancements to the baseline system in response to FAA recommendations made after test and evaluation during the year. As part of system tests, JPL routinely processes data from turbulence-detecting ground weather radars at the FAA testing facility in Norman, Oklahoma.

A Real-Time Weather Processor comprising 14 interconnected computers from Digital Equipment Corporation will be deployed at each of the FAA's 23 Air Traffic Control Centers. Air traffic controllers will be able to view, in near-real-time, a mosaic of data from advanced weather radars that detect clear-air turbulence for en route flights.

The Real-Time Weather Processor is scheduled for acceptance testing in 1992, followed by delivery to the FAA for operations testing. JPL is responsible for the first prototype; the remaining systems will be built by a contractor using hardware and software from the Laboratory.

ANALYSIS AND TRAINING SYSTEMS PROJECT

JPL originally supplied the Corps Battle Simulation system as an Army corps- and division-level battle trainer simulating

800 ground units. The system allows corps, division and brigade commanders and their staffs to exercise wartime duties in simulated battle drills. In 1991, it was expanded to manage 4,000 units and linked to an existing theater-level ground warfare simulation system to support Caravan Guard, a U.S. Army summer exercise in Europe. JPL engineers next plan to extend the system's capabilities so that it can manage 15,000 to 20,000 units (six corps) and then a theater-level exercise.

The system was used extensively during the Desert Shield period, first at Fort Leavenworth and later in Saudi Arabia, as a tool in evaluating operational plans and tactics. While not specifically designed for that purpose, the system nevertheless helped Army planners evaluate alternate courses of action. As part of a Department of Defense initiative to develop simulation interface standards, the Army is preparing to link the Corps Battle Simulation system with the Air Force's training simulation for joint training exercises.

ALL SOURCE ANALYSIS SYSTEM PROJECT

In 1991, the final version of the All Source Analysis System was delivered to the Army at Fort Hood, Texas. The system uses computer and communications technology to automate intelligence-analysis processes and is designed for deployment at the division or corps level. Following extensive tests, the Defense Intelligence Agency accredited the system for operation.

During the year, a JPL-led team completed over one million lines of code for the system's fieldable software. Technicians fabricated several improved versions of the principal hardware components, including a communications module, a computer module and an analyst workstation. Army field testing and evaluation will take place through most of 1992. JPL will continue to maintain software into 1994 and deliver the remaining complement of hardware. Additionally, the Laboratory will continue to enhance the software for increasingly capable versions of the system.

SP–100 PROJECT

The Space Power–100 (SP–100) project, sponsored by the Department of Energy, the Strategic Defense Initiative Organization and NASA, is developing nuclear electric power systems for Earth-orbital and deep space exploration missions and for use in facilities on the Moon and Mars. The SP–100's thermoelectric converter transforms heat generated by a nuclear reactor into electricity. The thermoelectric cells in the converter produce approximately 25 times the power of a similar device currently aboard the Galileo spacecraft.

During 1991, JPL developed a sapphire electrical insulator for the thermoelectric cells. This was a major technical accomplishment considering the high electric-field gradients (10,000 to 20,000 volts per millimeter) that the insulator must accommodate and the extremely high temperatures (over 1,093 degrees Celsius) at which it must operate for up to 10 years. Researchers also made significant progress in improving the operating efficiency of the semiconductor materials that constitute the thermoelectric cells. The performance of both N-type and P-type silicon–germanium material was boosted by 20 percent in tests of a pre-prototype cell for over 600 hours.

Development of nuclear subsystem elements for the power systems continued with successful tests of control drive components and a full-scale hydraulic flow test of the reactor. During life tests in Department of Energy test reactors, researchers achieved their goal of 6-percent burnup with fuel pins using prototype fuel and reached 3-percent burnup with pins having both prototype fuel and prototype cladding. Scientists also conducted a successful vibration test of the SP-100 fuel pin.

TECHNOLOGY COMMERCIALIZATION

The Laboratory's Technology Affiliates Program offers U.S. firms ready access to JPL's technology base. The program is based on the principle that technology is most effectively transferred when participating industries identify their needs. JPL responds by facilitating direct contact between companies and Laboratory personnel. Thirty-nine companies have participated in the program, with over 75 technology-transfer tasks completed.

Like many other agencies, NASA participates in the Congressionally mandated Small Business Innovation Research program, an annual three-phase procurement designed to encourage small businesses that have inventive ideas. Once a year, NASA invites these companies to submit engineering and science proposals on ideas of interest to its field centers, including JPL. The potential commercial applications for a proposed idea are a compelling factor in its selection. Forty-five contracts, totaling about $9 million, were funded under this program through JPL in 1991.

SOLDIERS DEPLOY CAMOUFLAGING AND BARBED WIRE TO PROTECT THE MOBILE, COMPUTER-BASED ALL SOURCE ANALYSIS SYSTEM, WHICH CAN BE SET UP OR DISASSEMBLED IN JUST 30 MINUTES.

INSTITUTIONAL ACTIVITIES

JPL's mission is *to serve the nation* as a premier space science, engineering and applications laboratory. As part of Caltech, a leading scientific research and educational institution, the Laboratory strives to maintain the standards of excellence consistent with that relationship. Recognizing our obligation to serve the national interest, *our staff is motivated by* the challenges of carrying out technically challenging projects of national significance. JPL is dedicated to providing a stimulating environment that encourages *innovation, and* our goal is to maintain, develop and enhance those attributes that contribute to the fulfillment of *our vision of the future*. Research and development costs for the fiscal year ending in September were $1.092 billion, a 4-percent increase from last year. Costs for NASA-*funded activities rose* 8 percent to $840 million. Costs for other activities dropped 7.5 percent to $252 million. The work force increased during the year to 6,359, compared with 6,114 in 1990 and 5,892 in 1989. Procurement obligations *during the fiscal year* totaled $661 million, 2 percent less than in 1990. These outlays included $604 million to business firms, including $148 million to small businesses and $24 million *to small, minority-owned businesses*.

THE MALL AREA REFLECTS JPL'S CAMPUS-LIKE ENVIRONMENT. AS PART OF CALTECH, THE LABORATORY CONTINUES TO STRIVE FOR THE HIGHEST STANDARDS IN SPACE SCIENCE, SYSTEMS ENGINEERING AND RESEARCH.

FORMER BRITISH PRIME MINISTER MARGARET THATCHER VISITS JPL. HERE, MRS. THATCHER AND JPL DIRECTOR DR. EDWARD C. STONE (CENTER) INSPECT IMAGES OF VENUS WITH MAGELLAN SCIENTISTS DRS. R. STEPHEN SAUNDERS AND ELLEN R. STOFAN.

FOR HIS OUTSTANDING LEADERSHIP AS PROJECT SCIENTIST FOR THE VOYAGER MISSION, JPL DIRECTOR DR. EDWARD C. STONE RECEIVES THE NATIONAL MEDAL OF SCIENCE FROM PRESIDENT GEORGE BUSH.

LABORATORY AWARDS

The Laboratory received the Exemplary Voluntary Efforts Award from the Department of Labor in recognition of innovative efforts to increase employment opportunities for minorities, women, individuals with disabilities, disabled veterans and veterans of the Vietnam era. JPL also received the Transportation Award of Excellence, a recognition by local governments of the Laboratory's outstanding efforts in reducing commuter vehicle trips.

SPECIAL HONORS

The following individuals and teams were honored during 1991:

National Medal of Science

Edward C. Stone, for outstanding leadership as project scientist for the Voyager mission and his experiments in the outer solar system.

William T. Pecora Award, NASA and Department of the Interior

Moustafa T. Chahine, for outstanding contributions to the understanding of Earth by remote-sensing technologies.

Jules G. Charney Award, U.S. Meteorological Society

Moustafa T. Chahine, for achievements in atmospheric sciences.

G. K. Gilbert Award, Geological Society of America

John Guest, for excellence in planetary geologic research.

Science Man of the Year Award, ARCS Foundation

Edward C. Stone, for outstanding contributions to planetary exploration.

Judith A. Resnik Award, Institute of Electrical and Electronics Engineers

Leslie J. Deutsch, for contributions to the theory and practice of deep space telecommunications and information processing.

Nelson P. Jackson Aerospace Award, National Space Club

Magellan and Galileo project teams

von Kármán Lectureship, American Institute of Aeronautics and Astronautics

John R. Casani

Lew Allen Awards for Excellence

- Randall R. Friedl
- Brian D. Hunt
- Robert W. Fathauer
- True-Lon Lin
- William R. McGrath

Elected Fellow, American Physical Society

Lew Allen

Elected Fellow, American Institute of Aeronautics and Astronautics

Edward C. Stone

Elected Fellow, American Astronautical Society

Peter T. Lyman

Medal for Engineering Excellence, Institute of Electrical and Electronics Engineers

Charles Elachi

Humboldt Foundation Prize, Germany

Robert F. Landel, for outstanding scientific contributions to the field of polymers.

Peter Mark Memorial Award

William J. Kaiser, for innovative applications of electron tunneling techniques.

Thomas R. Benedict Memorial Award

Anil P. Thakoor, Silvio P. Eberhardt and Taher Daud, as co-authors of "Electronic Neural Network for Dynamic Resource Allocation," the outstanding paper of the Eighth AIAA Computers in Aerospace Conference.

NASA HONOR AWARDS

The annual NASA Honor Awards are given in recognition of outstanding achievements by individuals and teams. The following awards were presented to JPL employees in 1991:

Distinguished Service Medal

- John R. Casani

Outstanding Leadership Medal

- Neal E. Ausman, Jr.
- Thomas R. Gavin
- Carl W. Johnson
- Matthew R. Landano
- William J. O'Neil
- Richard J. Spehalski
- Robertson Stevens
- Clayne M. Yeates (posthumously)

Exceptional Achievement Medal

- Anthony J. Gainsborough
- Phyllis M. Herzer
- Patricia A. McGuire
- Douglas J. Mudgway
- Richard L. Schieffelin
- Ursula M. Schwuttke
- I. Dale Wells
- Roger M. Williams

Exceptional Scientific Achievement Medal

- Samuel Gulkis
- Gregory A. Nelson
- Steven J. Ostro

Exceptional Engineering Achievement Medal

- Tien T. Nguyen
- Brian H. Wilcox

Exceptional Service Medal

- Arden L. Acord
- Jerrold E. Bailey
- Robert C. Barry
- Raymond A. Becker
- Antal K. Bejczy
- David E. Bell
- Morris M. Birnbaum
- N. Talbot Brady
- Barbara D. Brown
- Garry M. Burdick
- Russell K. Caplette
- Christopher Carl
- Dennis G. Carpenter
- Waldo J. Castellana
- A. Earl Cherniack
- Janis L. Chodas
- Denise M. Cohen
- M. Joseph Cork
- Gary G. Coyle
- Louis A. D'Amario
- Harry A. Davis
- Ronald F. Draper
- James A. Dunne
- James K. Erickson
- William G. Fawcett
- Joseph A. Gleason
- Milton T. Goldfine
- Morris L. Greenfield
- Richard G. Haga
- Maynard G. Hine
- William F. Hoffman
- Dorothy J. Huffman
- William A. Imbriale
- Michael H. Jacobs
- Patti A. Jansma
- Torrence V. Johnson
- John C. Kievit
- William E. Kirhofer
- Peter M. Kobele
- Robert W. Kocsis
- Wayne H. Kohl
- Sanford M. Krasner
- Margo P. Kuhn
- Gerald R. Lane
- Thomas J. Laney
- Charles L. Lawson
- William E. Layman
- Kim Leschly
- Gregory C. Levanas
- Frank C. Locatell, Jr.
- John Robert Locke
- Guy K. Man
- James C. Marr
- John C. McKinney
- Carol L. Miller
- Robert T. Mitchell
- Patricia M. Molko
- Robert M. Nelson
- Robert D. Rasmussen
- Ralph J. Reichert
- James T. Renfrow
- William M. Ruff
- Moktar A. Salama
- Joseph L. Savino
- John W. Schlue
- L. Tom Shaw
- James W. Stultz
- R. Frank Tillman
- Jean D. Walker
- Allen E. Wolfe
- Jervis L. Wolfe
- Neil J. Yarnell
- William J. York, Jr.
- John E. Zipse

Certificate of Appreciation

- Theodore A. Balzar
- Mendel D. Hill
- Steve S. Kuan
- Judith E. Morrissey
- Richard F. Rathcke
- Christopher S. Yung

MINORITY SCIENCE AND ENGINEERING INITIATIVES

During the fiscal year, JPL's Minority Science and Engineering Initiatives Office intensified efforts to forge new partnerships with minority colleges and universities across the country. The goal of these collaborative programs is to broaden and diversify the pool of science and engineering talent available to NASA for the benefit of the U.S. space program. The Minority Science and Engineering Initiatives Office also supports the Caltech Minority Undergraduate Research Fellowship Program.

Historically Black Colleges and Universities Initiative

JPL made considerable progress under Executive Order 12677, signed in 1989 by President George Bush, to create new educational and training opportunities for students attending the nation's Historically Black Colleges and Universities (HBCUs). The Laboratory signed new memoranda of understanding with North Carolina A&T State University in Greensboro; Central State University in Wilberforce, Ohio; Florida A&M University in Tallahassee, and Hampton University in Hampton, Virginia.

In conjunction with the Pasadena Community Education Outreach Exhibition, JPL hosted the third annual Technical Interchange Workshop to explore issues of minority recruitment in engineering and Earth and physical sciences. The workshop drew over 200 participants this year, including university officers, science and research faculty members and representatives of Federal agencies affiliated with minority university programs.

Under Operation Pipeline, nine high school students from the Pasadena area were awarded undergraduate scholarships to attend the HBCUs of their choice. Operation Pipeline is supported by OAO Corporation, a NASA and JPL contractor, and the J. Mosely Trust.

The Summer Technical Internship Program was greatly expanded to support 32 summer student interns from HBCUs and other minority institutions. Students worked in various technical research areas such as communications, imaging systems, spacecraft navigation and satellite mapping of the oceans.

Three new fellowships and one full-time NASA scholarship were awarded to JPL employees under the JPL Minority Fellowship Program. Since its inception in 1989, the fellowship program has had nine recipients, all highly successful in academic studies. Two fellows graduated with degrees in electrical engineering and computer science this year; a third was nearing completion of her master of science degree in electrical engineering.

Hispanic Educational Excellence Initiative

Under this initiative, two predominantly Hispanic institutions — California State University, Los Angeles, and the University of Texas, El Paso — entered into collaborative agreements with JPL during the Laboratory's Technical Interchange Workshop. JPL also established faculty fellowship programs and employment opportunities with other Hispanic-serving institutions and identified two Hispanic fellows for support during undergraduate and graduate studies at the University of New Mexico and Florida A&M University.

Four collaborative research projects that will be based at Hispanic-serving institutions were also funded this year. Two research clinics were established at California State University, Los Angeles. A third joint research project will be carried out at the University of Texas, El Paso. Another research and training program at the Texas school, called Continuous Engineering Science and Technology Advancement for Underrepresented Minorities (CUESTA), was also expected to start.

Native American Initiative

The Sacred Mountain Scholars Program, a collaborative academic training program jointly sponsored by JPL and Northern Arizona University's College of Engineering and Technology, began its third year. The program supports Hopi, Navajo and Apache undergraduate students from Arizona, Utah and New Mexico. Eligible students majoring in science, engineering, business or other disciplines pertinent to JPL's mission are supported by summer training opportunities each year at the Laboratory.

National Physical Science Consortium

The Laboratory joined this fellowship program for women and minorities in the physical sciences, which is designed to provide JPL employees with additional ways of obtaining educational scholarships. JPL also joined other NASA centers and corporations in supporting the National Consortium for Graduate Degrees for Minorities in Engineering, Inc., which provides graduate educational opportunities for minority students working toward masters and doctoral degrees in sciences and engineering.

EDUCATIONAL OUTREACH

JPL and Caltech are cosponsors of the newly formed Southern California Space Academy, a "school within a school" for students in the Pasadena Unified School District who are interested in the applied sciences and engineering. Last fall, the Space Academy began with more than 80 high school students in grades 10, 11 and 12 at Pasadena's John Muir High School.

JPL's Educational Outreach Program was awarded two National Science Foundation (NSF) grants to further develop and diversify its teacher training programs in science and technology. The first was a three-year follow-up grant awarded to the NASA–JPL Comfortable Approach to Teaching Science II (CATS–II) program, a project involving NASA, JPL and California Polytechnic University at Pomona, to expand a science training program for elementary school teachers. As part of CATS–II, JPL's public education staff will assist local educational teams, Native American teams and others from Historically Black Colleges and Universities (HBCUs) in setting up local CATS programs. The first HBCUs to open CATS "clone centers" will be Fayetteville State College in North Carolina and the University of the District of Columbia. The program's HBCU component is supported by the Minority Science and Engineering Initiatives Office.

The second NSF grant brought JPL together with the Upland Unified School District in Upland, California, in a joint training program entitled "Terracorps." Designed for middle schools, Terracorps is an interdisciplinary, thematic curriculum using ecology as the general theme of major studies in grades six to eight. The JPL educational outreach staff is helping to write the curriculum and will train teachers in its use.

JPL's Adopt-A-School program involved sixth-, seventh- and eighth-grade students at Charles W. Eliot Middle School in Altadena in field trips to local museums and observatories and to such NASA operations as the Dryden Research Facility and the Goldstone Deep Space Communications Complex.

DISTINGUISHED VISITING SCIENTIST PROGRAM

The Distinguished Visiting Scientist Program promotes interchange among researchers worldwide and Caltech and JPL scientists and engineers. The program aims to strengthen and advance areas of research that are of particular interest to JPL by providing a forum for the exchange of ideas, research methods and technical expertise.

The following individuals were appointed as distinguished visiting scientists in 1991 and have spent from 2 to 12 months at JPL offering insights and expertise in the indicated fields:

Superconductivity and Neural Networks

Ivar Giaever
Rensselaer Polytechnic Institute
Troy, New York

Satellite Observations With General Circulation Models to Simulate Ocean Conditions

George S. Philander
Princeton University
Princeton, New Jersey

Scanning Tunneling Microscopy

Heinrich Rohrer
IBM Zürich Research Laboratory
Zürich, Switzerland

Electrical Engineering and Materials Science

Michael Spencer
Materials Science Research Center of Excellence, Howard University
Washington, D.C.

Radio and Submillimeter Astronomy

Robert W. Wilson
AT&T Bell Laboratories
Holmdel, New Jersey

SENIOR RESEARCH SCIENTIST

The position of Senior Research Scientist is awarded to scientists who have shown outstanding achievement and leadership in their fields. Researchers serve in this capacity from 18 months to 2 years. One individual received this honor in 1991:

Infrared Astrophysics

Michael W. Werner

PATENTS AND TECHNOLOGY UTILIZATION

During the fiscal year, the Office of Patents and Technology Utilization prepared, evaluated and forwarded to NASA reports on 287 inventions and technical innovations resulting from JPL work. The office answered 59,864 requests from industry and the public for technical information on JPL inventions and innovations published in the NASA-sponsored monthly *Tech Briefs*. During the year, 234 entries from JPL were published in *Tech Briefs*, representing 37 percent of the NASA-wide total. The U.S. Patents Office issued 46 patents to Caltech and NASA on inventions developed at JPL. NASA granted the following awards for JPL inventions:

Exceptional Award

John C. Peterson, Jesus O. Tuazon, Moshe Pniel and Don Lieberman shared $10,000 equally for *Concurrent Hypercube Computing System With Improved Message Passing.*

Major Awards

David J. Atkinson and Mark L. James shared $2,000 equally for *Star-Tool — an Environment and Language for Expert Implementation.*

James R. Janesick received $1,000 for *Multipinned Phase Charge-Coupled Device.*

DIRECTOR'S DISCRETIONARY FUND

The Director's Discretionary Fund (DDF) is the major resource for innovative and seed efforts that do not receive conventional task-order funding. For 1991, the DDF level of funding was $3.5 million.

The fund initiated 22 new research tasks, extended the objectives of 9 ongoing tasks — awarding more funds to them — and provided modest assistance to several other support efforts. Proposals that are

eligible for DDF monies cover a broad range of sciences and technologies. Areas of recent emphasis have included advanced microelectronics, automation and robotics, advanced observational techniques and technology for advanced optical systems.

The DDF recognizes important mutual benefits from collaboration with faculty and students at Caltech as well as other academic institutions, so cooperation is specifically encouraged. Ten new and extended principal tasks funded this year involve 24 university faculty collaborators.

PRESIDENT'S FUND

The Caltech President's Fund provides a second, although smaller, source of discretionary funding. Currently at a level of $1 million a year, the fund comes from Caltech and NASA resources on a dollar-for-dollar matching basis and is administered by Caltech. An explicit objective of the President's Fund is to encourage the interest and participation of university faculty and students in JPL research activities, affording JPL staff members an opportunity for close association with research workers from the university community. The President's Fund provided resources for 15 new collaborative tasks this year.

ADDITIONAL ACTIVITIES

Metric Conversion

Following NASA guidelines, JPL initiated its program of metric conversion during the fiscal year. The international system of units will be incorporated into all new spaceflight projects unless waived for specific project reasons.

Environmental Cleanup

JPL complied with requirements of the Environmental Protection Agency's Superfund program by spearheading efforts in 1991 to identify sites of possible soil contamination on its 176 acres. A remedial investigation and feasibility study is assessing possible solutions and developing a cleanup plan for proposal to the Agency in 1993.

Disaster Preparedness

JPL's Multihazard Emergency Response Plan was tested in June when an earthquake measuring 5.8 on the Richter scale shook the Pasadena area. Security and Plant Protection staff activated the Emergency Operations Center, evacuated buildings and kept employees informed of the situation.

Caltech Centennial

JPL celebrated Caltech's 100th anniversary with a weekend Expo, which was attended by 20,000 people. As part of the Centennial activities, past and present JPL directors and Caltech presidents gathered for a special symposium at Caltech to discuss the future of the U.S. space program.

Commemorative Stamps

In October, the U.S. Postal Service issued a new 10-stamp series at JPL. The stamps commemorate space exploration and depict automated spacecraft such as Mariner, Pioneer, Viking and Voyager. Postmaster General Anthony M. Frank and Pasadena Postmaster José L. Castellanos joined JPL Director Edward C. Stone in introducing the stamp set.

Foreign Dignitary

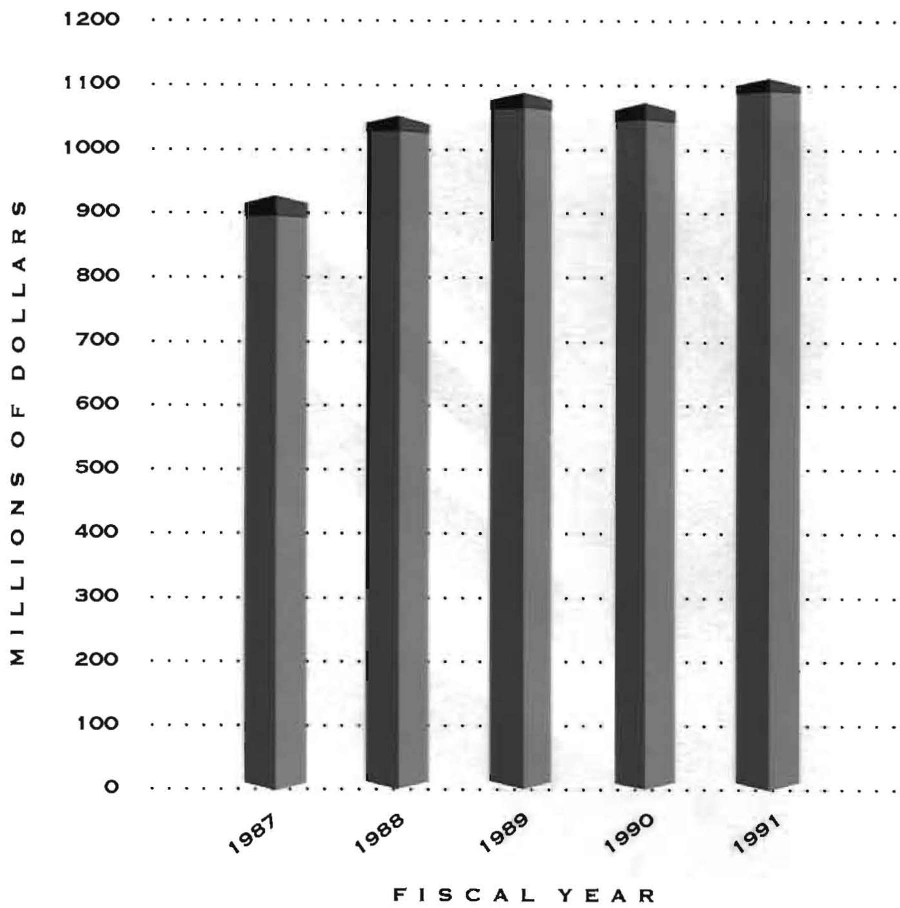
Former British Prime Minister Margaret Thatcher and her party were given a tour of JPL facilities by Director Edward C. Stone and senior Laboratory managers during a visit in February. They were greeted on the mall by hundreds of employees. Ms. Thatcher was presented with a mounted print of a Voyager 2 color image of Neptune.

THIS STREAMLINED PROFILE STANDS IN SHARP CONTRAST TO JPL'S MODEST BEGINNINGS — A SMALL BAND OF STUDENTS WHOSE EXPERIMENTS NEAR PASADENA'S ARROYO SECO FIRST PROVED THE FEASIBILITY OF ROCKET ENGINE DEVELOPMENT.

TOTAL COSTS

CONSTRUCTION OF FACILITIES

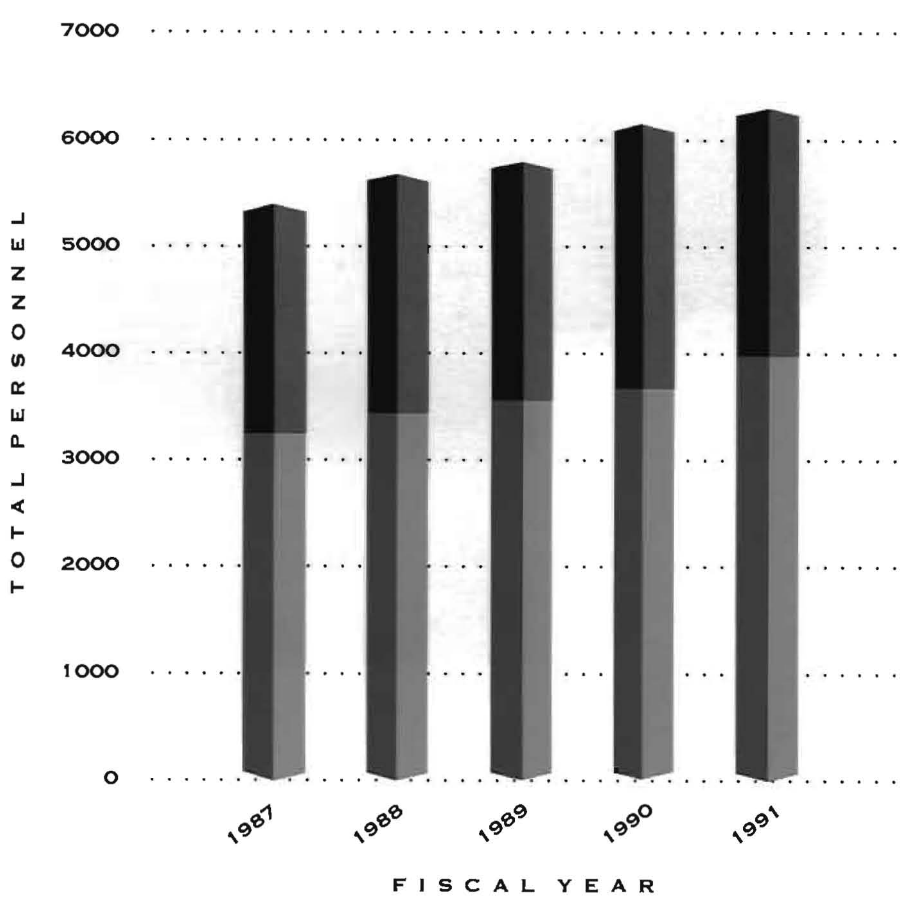
RESEARCH AND DEVELOPMENT



PERSONNEL

SUPPORT PERSONNEL

ENGINEERS AND SCIENTISTS



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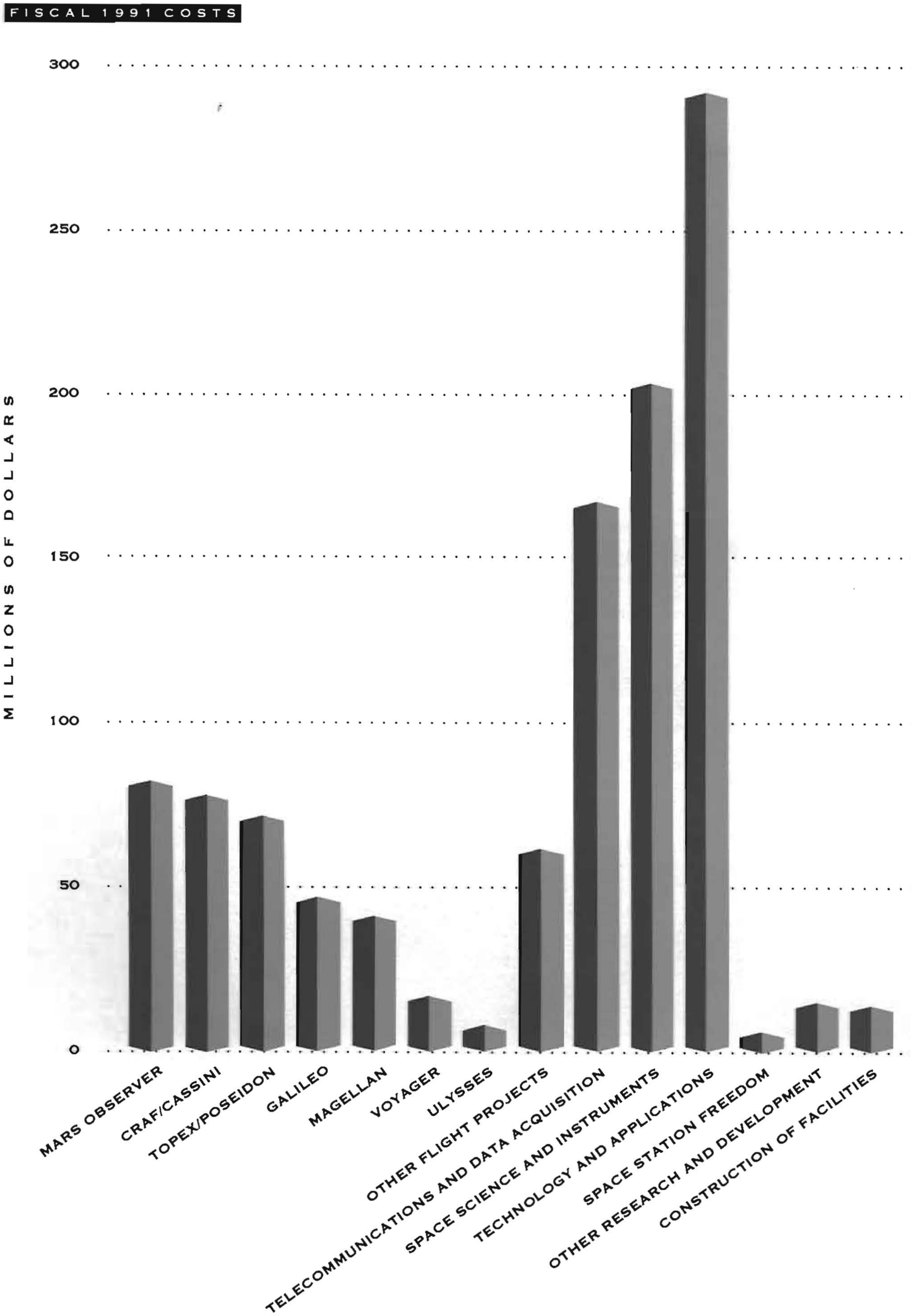

FISCAL 1991 COSTS
300
250
200
150
100
50
0
MILLIONS OF DOLLARS
MARS OBSERVER
CRAF/CASSINI
TOPEX/POSEIDON
GALILEO
MAGELLAN
VOYAGER
ULYSSES
OTHER FLIGHT PROJECTS
TELECOMMUNICATIONS AND DATA ACQUISITION
SPACE SCIENCE AND INSTRUMENTS
TECHNOLOGY AND APPLICATIONS
SPACE STATION FREEDOM
OTHER RESEARCH AND DEVELOPMENT
CONSTRUCTION OF FACILITIES

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Moustafa T. Chahine
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John R. Casani
Assistant Laboratory Director
Flight Projects

Kirk M. Dawson
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Assistant Laboratory Director
Telecommunications and
Data Acquisition

Charles Elachi
Assistant Laboratory Director
Space Science and Instruments

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Harry M. Yohalem
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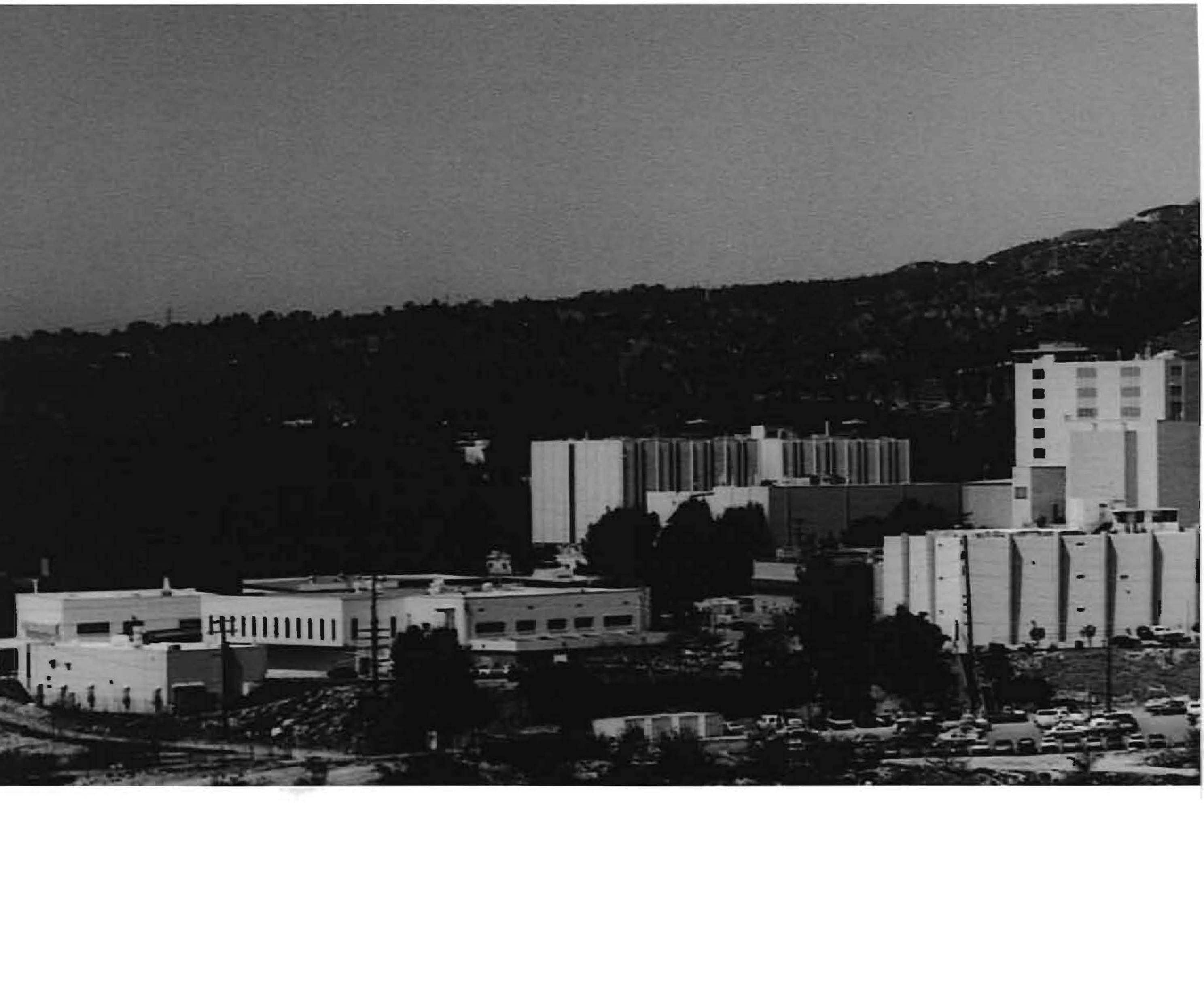

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